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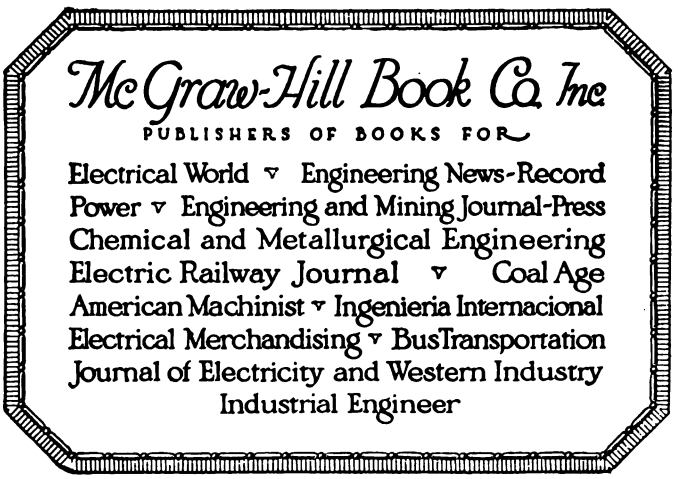

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ELECTRICAL ENGINEERING LABORATORY EXPERIMENTS

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PREFACE

If the student taking an electrical engineering laboratory course is required to rely on his own resources, exert his own initiative and do some original thinking, that course will stand out in his memory as one of the few in which he really accomplished the end in view; namely, a natural growth of reasoning power, the power of keen and accurate observation, the ability to analyze and draw conclusions and a knowledge of the fundamentals involved in the construction and operation of electrical machinery.

To make laboratory teaching effective, the student should be carefully supervised at the beginning of his course in order that he may learn as rapidly as possible the fundamentals of electrical testing, and use them as his tools for the more advanced work. He should then be assigned work which will require original thinking, and be required to rely more or less upon his own resources. He should be encouraged to hunt up some problem in which he is particularly interested and tackle it as a real research proposition. In this way he will unconsciously exercise his initiative and prefer to rely upon his own resources.

During the preparation of this book the writers have had the above philosophy constantly in mind and believe the book to be sufficiently flexible for adaptation to almost any Electrical Engineering Laboratory Course.

This book is the result of an extended period of growth and experience. The original notes were written by Professor R. R. Lawrence and published in neostyle form in 1903 for use in the Lowell Institute for Industrial Foremen. These notes were later revised and enlarged by Professor Lawrence in 1907, and again revised and enlarged by him and published in book form in 1914. Professors Lawrence and C. W. Green in 1914 took a portion of the material, revised it and published it for use in connection with the courses in Electrical Engineering Laboratory at the Massachusetts Institute of Technology. In 1919 the authors

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revised and enlarged it and had it published as by the Electrical Engineering Department of the Massachusetts Institute of Technology. At this time with the help of Professor F. A. Laws, four experiments on Electrical Measurements were introduced. The authors are greatly indebted to the above-mentioned men for their helpful criticisms and suggestions.

Due to the apparent demand of other schools for a book of this kind, the authors have undertaken the work of more or less completely revising it, the better to satisfy the requirements of other engineering schools.

This work does not purport to cover the field of electrical measurements. In order, however, to make the book of value to other teachers, the authors deemed it advisable to include some of the more fundamental experiments relating to electrical measurements.

In writing up the experiments the authors have endeavored to give the theory involved in sufficient detail so that reference books will in general not be required, but for the benefit of those who desire more detailed information, numerous references have been given to certain of the standard texts, to the transactions of the A.I.E.E. and to the Electrical Engineering Handbooks.

The procedure required to obtain certain desired results is outlined in detail. At the end of the procedure is a list of results which can be determined from the data taken by following the outlined procedure. In order to easily obtain variations of the experiments suggested results required are appended for the use of teachers who do not care to follow the procedure as outlined. There are also appended problems, the solution of which requires the taking of certain additional data.

The lists of Results Required attached to each experiment is of some length, the object being twofold. First, in various schools the laboratory periods will necessarily vary in length. The instructor therefore may assign only as many of the Results Required as the student will have time to take data for in the time available. Others of the Results Required may be assigned at a later exercise if it is desired to devote more time to the particular experiment at hand. Second, the lists of Results Required were made of some length in order that variety might be had in not requiring each group to cover precisely the same ground and so that variation might be had from year to year.

Chapters I to III, inclusive, contain a limited amount of general information required by all students working in an electrical laboratory. The chapter dealing with electrical measurements and measuring devices is necessarily brief, due to the fact that this ground is well covered in the standard electrical engineering texts. It is put in simply for hasty reference while in the laboratory.

The authors are convinced that the preliminary calculated estimation of instrument ranges should be required for nearly all tests. A great deal of time is wasted by guessing the instrument ranges because a student does not have the necessary experience back of him. The table of average losses together with the typical examples of calculated estimations should enable a beginner to choose his instruments with a fair degree of accuracy.

C. W. RICKER.
C. E. TUCKER.

CAMBRIDGE, MASS.,
November, 1922.

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TABLE OF SYMBOLS

A' = Fictitious armature reaction, including real armature reaction and effect of the leakage reactance, expressed in amperes or ampere turns.

a = Ratio of transformation (always unity or greater) or number of parallel paths in an armature.

B = Balance reading.

B_o = Net balance reading.

C = Capacitance.

E = Electromotive force or luminous flux density expressed in lumens per unit area or in foot or meter candles.

E_a = Armature induced voltage.

E_a' = Synchronous-generator open-circuit voltage corresponding to full-load field current.

E_a'' = Synchronous-generator terminal voltage plus the effective-resistance drop.

F = Net balance reading or impressed field of a synchronous generator expressed in amperes or ampere turns, or light flux in lumens.

f = Frequency in cycles per second.

I = Current.

I_a = Armature current.

I_{a_g} = Generator armature current.

I_{a_m} = Motor armature current.

I_b = Blocked current of an induction motor for the impressed voltage V_t.

I_b' = Blocked current of an induction motor for the impressed voltage V_b.

I_C = Current in capacity reactance.

I_d = Candle-power in indicated direction.

I_f = Shunt field current.

I_{f_g} = Generator field current.

I_{f_m} = Motor field current.

I_H = Transformer high-tension current.
I_h = Mean-horizontal candle-power.
I_L = Line current, current in an inductance or transformer low-tension current.
I_m = Total motor current.
I_n = No-load current of an induction motor.
I_o = Current corrected for instrument losses
I_P = Transformer primary current.
I_p = Phase current.
I_R = Current in resistance R.
I_r = Current in resistance r.
I_S = Transformer secondary current.
I_s = Series field current or mean-spherical candle-power.
K = Constant of a watthourmeter.
L = Inductance.
L_e = Equivalent inductance.
n = Speed in revolutions per minute.
N_g = Number of turns on generator side of dynamotor.
N_m = Number of turns on motor side of dynamotor.
P = Electric power.
P_a = Armature copper loss.
P_b = Belt loss or blocked input to induction motor with impressed voltage V_t.
P_b' = Blocked input to induction motor with impressed voltage V_b.
P_{Cu} = Total copper loss in a machine.
P_f = Field copper loss.
P_{f+w} = Friction and windage loss.
P_H = Power at high-tension terminals of a transformer.
P_{h+e} = Iron loss due to hysteresis and eddy currents.
$P_{(h+e)_s}$ = Core loss in alternator due to load current.
P_L = Power at low-tension terminals of a transformer.
P_n = No-load input to induction motor.
P_o = Indicated watts corrected for instrument losses.
P_P = Transformer primary power.
P_S = Transformer secondary power.
P_{SP} = Stray power loss.
P_t = Total power loss in any machine.
p = Number of poles.
R = Resistance.

R'' = Resultant field of a synchronous generator expressed in amperes or ampere turns.
R_a = Armature resistance including brushes.
R_{a_g} = Generator armature resistance.
R_{a_m} = Motor armature resistance.
R_b = Resistance of brushes.
R_C = Equivalent series resistance of condenser.
R_e = Effective resistance.
R_{eH} = Equivalent resistance of a transformer referred to high-tension winding.
R_{eL} = Equivalent resistance of a transformer referred to low-tension winding.
R_f = Shunt field or alternator field resistance.
R_H = Ohmic resistance of high-tension winding of a transformer.
R_L = Ohmic resistance of low-tension winding of a transformer or resistance of an inductance coil.
R_{oh} = Ohmic resistance.
R_s = Resistance of a series field.
R_t = Resistance at temperature t.
r = Radius of a pulley.
r_a = Ammeter resistance.
r_p = Wattmeter potential circuit resistance.
r_v = Voltmeter resistance.
r_w = Wattmeter current coil resistance.
S = Spherical reduction factor.
s = Slip of an induction motor in r.p.m. or per cent. of synchronous speed.
T = Torque in pound-feet.
t = Time in seconds.
V = Potential difference or voltage.
V_b = Voltage impressed on induction motor when blocked.
V_C = Voltage drop across a condenser.
V_f = Voltage impressed on an alternator field.
V_g = Generator terminal voltage.
V_H = Transformer high-tension voltage.
V_L = Voltage drop across inductance coil or transformer low-tension voltage.
V_m = Motor terminal voltage.
V_P = Transformer primary terminal voltage.
V_R = Voltage drop across resistance R.

V_s = Transformer secondary terminal voltage.
V_t = Terminal voltage.
V_z = Impedance voltage of a transformer.
W = Weights on brake pan.
X = Inductive or capacitive reactance.
X_C = Capacitive reactance.
X_{eH} = Equivalent reactance of a transformer referred to the high-tension side.
X_{eL} = Equivalent reactance of a transformer referred to the low-tension side.
X_L = Inductive reactance.
X_s = Synchronous reactance per phase.
Z = Number of armature inductors or impedance.
Z' = Armature constant $= \frac{pZ\,10^{-8}}{a\,60}$.
Z_{eH} = Equivalent impedance of a transformer referred to the high-tension side.
Z_{eL} = Equivalent impedance of a transformer referred to the low-tension side.
Z_s = Synchronous impedance per phase.

GREEK SYMBOLS

α = Resistance temperature coefficient.
γ = Conductivity or specific conductance.
Δ_t = Temperature rise in degrees centigrade.
η = Efficiency.
θ = Phase displacement of current vector with respect to voltage vector, i.e., power-factor angle.
θ_b = Blocked power-factor angle of an induction motor.
θ_n = No-load power-factor angle of an induction motor.
λ = Flux linkages.
ρ = Resistivity or specific resistance.
ϕ = Magnetic flux in maxwells.
ω = Angular velocity in radians per second.

ELECTRICAL ENGINEERING LABORATORY EXPERIMENTS

CHAPTER 1

MEASURING DEVICES AND THEIR APPLICATIONS

Direct-current Ammeter [1] and Voltmeter.[2]—The d'Arsonval [3] type of instrument is almost universally used when making measurements in direct-current circuits. It consists of a moving element situated in a magnetic field which is established by a permanent magnet. The moving element is a coil of fine wire mounted on a spindle. When a current is passed through the coil a turning moment is produced by the reaction of the current and magnetic field. This turning moment is balanced by spiral springs. By properly designing the magnetic circuit and springs the deflection of the moving element may be made proportional to the current in the element.

A typical moving element would be deflected to full scale by a current of 20 to 100 milliamperes. The voltage drop through a moving element for full scale deflection is usually from 20 to 100 millivolts. Since in an element of fixed resistance and in which there is no generated e.m.f. the current is directly proportional to voltage, the scale may be calibrated in either milliamperes or millivolts, thus making the instrument a milliammeter or a millivoltmeter. If then the instrument is to be used as an ammeter the range is increased by shunting the moving element by a resistance; then knowing the resistance of this shunt the current

[1] LAWS, "Electrical Measurements," p. 55.
[2] LAWS, "Electrical Measurements," p. 236.
[3] LAWS, "Electrical Measurements," p. 32.

in the shunt and moving coil can be found and the meter calibrated to read directly in amperes. If the instrument is to [1] used as a voltmeter the range is proportional to the total resistance and any desired range may be obtained by adjusting the amount of resistance in series with the moving element

A milliammeter, therefore, does not differ greatly from millivoltmeter, in fact, millivoltmeters are commonly supplied with shunts thus making them adaptable for the measurement of current. They may also be supplied with a high resistance for connecting in series with them when used for measuring higher voltages.

All ranges of any one type of ammeter usually have the same millivolt drop for full scale deflection. The power taken by the instrument including shunt for full scale reading is, therefore, proportional to its full scale reading. Voltmeters having similar moving elements have a resistance proportional to the full scale reading and since they take the same current for full scale reading, the power is proportional to that full scale reading.

The power taken at fractional scale readings by ammeters a given type and make is proportional to the square of the reading in amperes and inversely proportional to the full scale reading, and the power taken at fractional scale readings by voltmeters of a given type and make is proportional to the square of the reading in volts and inversely proportional to the full scale reading.

Alternating-current Ammeter [1] and Voltmeter.[2]—Alternating-current ammeters and voltmeters usually employ the iron-vane, dynamometer or hot-wire principle. The moving element of the iron-vane type consists of a soft iron vane which is inclined to the axis of the moving element and also to the axis of the field coil. The field coil carries the current to be measured. It cannot be shunted as in the case of direct-current instruments on account of inductive effects and is, therefore, wound with many turns of fine wire or few turns of heavy wire depending on whether a small or large current is to be measured. Current [3] transformers are used to supply the higher range instruments in order to avoid the difficulty of contending with the heavy parts. A voltmeter is made by inserting resistance in series with a milliammeter as in

[1] LAWS, "Electrical Measurements," p. 71.
[2] LAWS, "Electrical Measurements," p. 239.
[3] LAWS, "Electrical Measurements," p. 563.

the direct-current case. The iron-vane type of ammeter is used in the majority of cases because it is cheaper and can be built for comparatively high ranges without the use of current transformers.

The dynamometer type instrument has a moving element similar to that of the d'Arsonval type but the magnetic field is produced by a fixed coil instead of by a permanent magnet. The fixed and moving elements are connected in series. This type can be shunted provided a special inductive shunt is used but it is not common practice for meters over 10 amperes capacity. Due to the difficulty involved in conducting current of more than a few amperes through the moving element this type of instrument cannot be employed in the larger sizes without the use of current transformers. This difficulty is obviously not met in the voltmeters. The dynamometer type works equally well for direct current, whereas the iron-vane type is not reliable for direct-current measurements due to the action of the earth's field on the iron vane and due to the peculiar magnetic characteristics of the iron.

The hot-wire[1] ammeter as its name implies depends upon the elongation of a heating element due to change in temperature. It is not a rugged instrument but it has the distinct advantage of not being subject to frequency errors. The deflection is a function of change in temperature alone and consequently a function of the r.m.s. value of current squared irrespective of the complexity of the current wave. It is of course equally good for the measurement of direct currents.

Ammeter and Voltmeter Scales.—The scales of direct-current ammeters and voltmeters of the d'Arsonval type are made uniform by designing the magnetic circuit so that the flux cutting the active sides of the moving element is in the plane of the element and of the same density for all positions of the element. Due to the uniform scale the zero reading correction may be applied to any scale reading.

The torque exerted on the moving element in a meter of the iron vane or dynamometer type is proportional to the current squared and a function of the deflection. The latter factor is determined by the design features. Scales of such meters are not

[1] A. W. PIERCE and M. E. TRESSLER, "Hot-wire Instruments," *Trans. A. I. E. E.*, 1912, p. 1591.

LAWS, "Electrical Measurements," p. 58 and p. 241.

uniform and are designed so that they are fairly open in the central portion of the scale where the majority of the readings occur. Due to non-uniformity of scale a zero correction of so many amperes or volts cannot be applied to other points on the scale. The correction must be expressed in linear measure or angular deflection in order to be correctly applied to readings higher up on the scale.

The hot-wire ammeter scale is similar to those of the iron vane and dynamometer types.

The majority of ammeters and voltmeters are equipped with zero adjustments so that the pointer may be easily set at zero prior to placing the instrument in circuit.

Instrument Errors Due to Stray Fields.—Any instrument should be shielded from stray fields. Some types are enclosed in soft iron cases for this purpose. The cheaper grades are as a rule not shielded and special care must be exercised when using them to eliminate any effect due to stray fields. This may be done by altering the position and noting if the deflection is a function of the position of the instrument.

In case there is any question as to whether a meter is shielded or not, this may generally be determined by weight, since a shielded meter due to the added iron weighs considerably more than the equivalent non-shielded meter.

Wattmeters.[1]—A wattmeter always consists of two separate parts: a series or current coil, and a potential coil. The current coil is placed either directly in one of the mains of the circuit in which the power is to be measured or in the secondary circuit of a current transformer which has its primary in one main. In this latter case, the current coil carries a current which is closely proportional to the main line current and the reading of the wattmeter must be multiplied by a proper constant. Current transformers are seldom needed for currents below 50 amperes except on high-tension lines, where they are used to insulate the instruments from the line voltage. In such cases potential transformers are also required to insulate the potential coils of the wattmeters from the line voltage and to step down the voltage. When both current and potential transformers are used, one end of the current coil of the wattmeter should be connected to one end of the potential coil and then grounded.

Ordinary non-inductive shunts cannot be used with any instru-

[1] LAWS, "Electrical Measurements," p. 303.

ments intended for use on alternating current circuits except instruments of negligible inductance, such as hot-wire ammeters.

There is always a large non-inductive resistance in series with the potential coil of a wattmeter. This resistance with the potential coil is placed in shunt across the line. Most of the drop in potential in this shunt circuit occurs in the series non-inductive resistance. In order, therefore, to keep the potential coil and the current coil of any wattmeter at the same potential, the end of the potential coil and not the end of the series resistance must be connected to the line containing the current coil. This precaution is especially important when power in circuits of high voltage is to

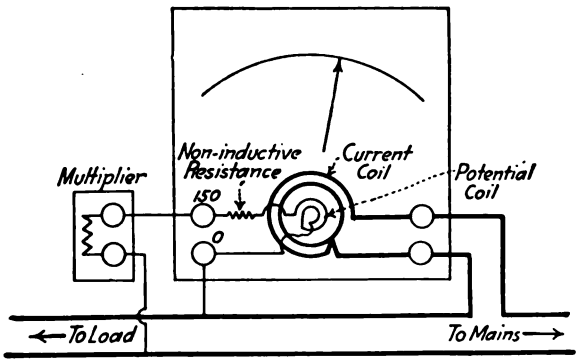


FIG. 1.

be measured, and if not observed, there will be great danger of breaking down the insulation between the two coils and burning out the instrument. Even if the instrument is not burned out the electrostatic attraction between the current and potential coils due to their difference of potential may cause false deflections.

When there is no diagram with a wattmeter showing its proper connections, the binding post of the potential-coil circuit which is marked zero should be connected to the line containing the current coil. The free terminal of the series non-inductive resistance which for voltages up to 150 volts, and sometimes up to 300 volts, is in the base of the instrument, is connected to the binding post marked with the potential limit. This is the post which should be connected to the line not containing the current coil. When it is necessary to extend the voltage range of a wattmeter by placing additional resistance in the potential-coil circuit, this resistance

must be connected to the terminal on the instrument marked with the voltage limit. Such a resistance is called an extension coil or multiplier. When a multiplier is used with a wattmeter, all the readings of the instrument must be multiplied by the proper constant. Multipliers are seldom used to increase the voltage range beyond 500 volts. For voltages above 500 transformers are generally used.

The correct connections for a wattmeter are shown in Fig. 1 and are indicated diagrammatically in Fig. 2. W is the current coil. The potential coil circuit, p, is, for convenience, shown outside of the current coil. It consists of a non-inductive resistance in series with the potential coil, and also includes the resistance of the multiplier in case one is used.

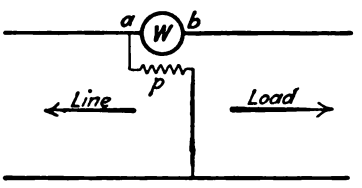


FIG. 2.

If a wattmeter reads backwards, the current coil should be reversed and not the potential-coil circuit. Reversing the potential-coil circuit will make the potential difference between the two coils equal to line potential. Some wattmeters have a button which reverses the potential coil without changing the location of the series resistance.

Wattmeters indicate the power due to the current in the current coil, and the voltage across the potential circuit. The free end of the potential circuit of a wattmeter may be connected to a as shown or may be connected to b. If connected to b, the wattmeter not only measures the power consumed by the load but also measures the power absorbed by the potential circuit of the wattmeter. This is equal to $\frac{V^2}{r_p}$ where V is the voltage of the circuit and r_p is the total resistance of the potential coil and its series resistance. This resistance is usually given on the instrument or its box. If the potential circuit is connected outside of the current coil or to a, the wattmeter will record the power delivered to the load plus the I^2r_w loss in its current coil. A wattmeter unless compensated always registers the power consumed in one of its coils but *never* the power consumed in both. The loss in the potential circuit is usually several times that in the current-coil circuit.

The correction for the heating loss in low range wattmeters

may amount to 5 or 6 per cent. and in exceptional cases to even 10 per cent. of the power recorded, but in commercial work as a rule, except when low-range instruments are used or instruments reading on very low power factor, corrections for heating losses are unnecessary. They should, however, never be overlooked. In core-loss measurements on transformers, corrections are usually necessary.

The size of a wattmeter can never be determined simply by the number of watts to be measured. It must always be fixed by the current and the voltage of the circuit irrespective of the power, for the coils of a wattmeter cannot stand more than a certain current without becoming overheated and burned out. Therefore the current rating and voltage limit, which are always marked on a wattmeter, should never be exceeded. If the power factor is low, the scale deflection also will be unavoidably low, but nothing can be done to improve this condition, except to use a wattmeter which is designed for low power-factor work. Such wattmeters have a full scale deflection which is only a fraction of the volt-ampere rating. The use of an instrument with a lower range current or potential circuit would result in burning it out.

In selecting a wattmeter for use on low power factor, it is important that one be chosen which will be used at as nearly as possible its full current and voltage ratings.

Since a wattmeter never indicates the current it is carrying or the voltage impressed upon its potential coil, it is always necessary to protect a wattmeter by an ammeter and a voltmeter. Quite frequently corrections have to be applied to the wattmeter readings for the power consumed by the heating in these instruments.

The current coil of a wattmeter should be treated as an ammeter and should, therefore, be protected by a short-circuit block.

The proper grouping of a wattmeter, an ammeter, and a voltmeter for measuring the power delivered to a load is shown in Fig. 3.

The voltmeter should always be placed next to the load, unless the exact voltage is not required, as in this position only will it give the correct voltage. If it is placed outside of the wattmeter at *a* it will read too high by the impedance drop through the ammeter and wattmeter current coil.

This impedance drop usually will be negligible but in case it is

not, correction for it cannot be made as the impedances of the instruments are not generally known.

The ammeter placed as shown between the voltmeter and wattmeter will read too high by the voltmeter current. Correction for this, however, can be applied if necessary. Since the voltmeter circuit is nearly non-inductive, the current taken by it will be its reading divided by its resistance. The ammeter reading should be corrected vectorially for this current. Except when the current to be measured is small, this correction is negligible.

If P, I and V represent the readings of the wattmeter, ammeter and voltmeter respectively and r_w, r_a and r_v the resistances of the wattmeter current coil, the ammeter, and the voltmeter

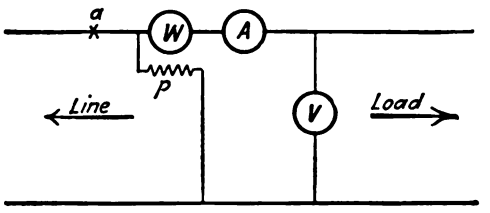


FIG. 3.

respectively, the true power, current and voltage of the load are given by the following expressions:

$$\text{True power} \quad = P_0 = P - I^2 r_w - I^2 r_a - \frac{V^2}{r_v}.$$

$$\text{True current, } I_0 = I - \frac{V}{r_v} \text{ (vector subtraction)} = \sqrt{I^2 - \frac{V^2}{r_v^2} - 2\frac{P_0}{r_v}}.$$

$$\text{True voltage} \quad = V.$$

In case the wattmeter potential coil is put in parallel with the voltmeter, the combined parallel resistance of r_v and r_p is $\frac{r_v r_p}{r_v + r_p}$ which is used in place of r_v in the expression for true current. The expression for true power is changed also.

NOTE.—The expression for the true current is derived from the solution of the vector diagram formed by the voltage, the true current, the ammeter current and the voltmeter current.

If the electrical output of any piece of apparatus is desired, the connections shown in the previous diagram are correct, provided what is marked load on the diagram is assumed to be the apparatus delivering the power. The power corrections in this case will be additive.

In general, the rule to be followed in correcting the wattmeter reading to give true power input is:

Subtract the losses in all current coils between the wattmeter potential circuit and the load and in all potential circuits whose current passes through the wattmeter current coil.

Compensated Wattmeter.—The compensated wattmeter reads true power directly provided the potential circuit is connected on the load side of the current coil and there are no instruments in circuit between the wattmeter potential coil and load. Compensation for the loss in the potential circuit is affected by inserting in the potential circuit an auxiliary coil having the same number of turns as the current coil and wound in parallel with the current coil. The current in the potential circuit then flows through both the current coil and the auxiliary coil and the connections are such that the net ampere turns in these two windings due to the potential-coil current is zero and consequently the deflection due to this is zero.

If the main current circuit is divided into two parts for series-multiple connection the auxiliary winding must also be split in order that the turns on the auxiliary winding may for either connection be equal in number to those on the main winding. No change in compensation is required for a change in resistance in the potential circuit, i.e., a change in voltage scale.

Measurement of Power in Three-phase Circuits.—The power in any three-phase circuit may be measured by either the three- or the two-wattmeter method.

The proper connections for the *three-wattmeter method* are shown in Fig. 4. The sum of the three-wattmeter readings is the true power in the circuit under all conditions of balance and power factor, provided the load, if Y-connected, does not have a neutral connection between the source of power and the load. If the wattmeters have equal resistances in their potential coil circuits, *a* will be

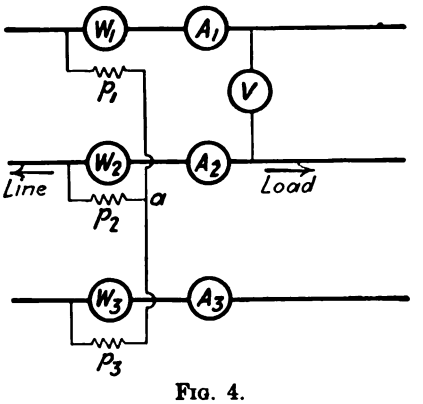


FIG. 4.

the true neutral point of the system. Under these conditions the wattmeters will read alike if the load is balanced. If the resistances of the potential coil circuits are not equal, the readings of the wattmeters will not be alike, but the algebraic sum of their reading will still give the true power for either balanced or unbalanced loads. The voltage limit of the potential coils should be at least equal to the voltage between the mains divided by the square root of three.

The power factor of an unbalanced three-phase circuit has little significance. If the circuit is balanced or nearly balanced the power factor is given by

$$\frac{P_1+P_2+P_3}{\sqrt{3}IV},$$

where P_1, P_2 and P_3 are the readings of the wattmeters W_1, W_2 and W_3 respectively, where I is the average line current and V is the average line voltage. If the voltage of the circuit is not exactly balanced, the voltmeter should be placed across the three phases in succession in order that the average voltage may be obtained. If the load is balanced two of the wattmeters may be omitted and their potential coils replaced by equivalent resistances. Three times the reading of the remaining wattmeter will give the power in the three-phase circuit. A box containing the equivalent resistances is known as a Y box. If the load has a neutral the power may be measured using the three wattmeters and connecting a to the neutral.

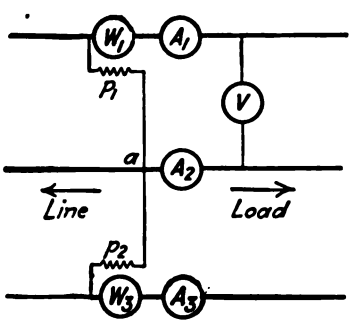


FIG. 5.

The proper connections for the *two-wattmeter method* are given in Fig. 5. The two wattmeters used in this method need not be similar in construction and resistance. They should, however, have equal current ratings and equal voltage ratings. The voltage limit of the potential coil circuits must be equal to, or slightly greater than, the voltage between the lines. The algebraic sum of the readings will give the true power in the circuit under all conditions of balance and power factor, provided the circuit does

not contain a neutral wire which extends back of the point at which the power is measured. The readings of the two wattmeters will not be equal even for balanced loads except for system power factors of unity and zero. Zero power factor for the system will, of course, never be reached in practice. For power factors above 50 per cent. both wattmeters will read positively and their readings should be added. Below 50 per cent. power factor, one wattmeter will read negatively and the true power will be the difference of the readings. The readings of both wattmeters will be positive if both wattmeters are similarly connected. If the connections of the current coil of one have to be reversed with respect to the connections of the current coil of the other in order to make both wattmeters read up scale, the reading of the wattmeter with the lesser reading should be marked negative and subtracted from the reading of the other. If the two wattmeters are of the same make and type, simple inspection will as a rule be sufficient to determine whether their connections are similar or dissimilar. If the two wattmeters are not alike, the easiest way to determine similar connections of the two instruments is to put both wattmeters in the same circuit and note the connections of the current coils which give up-scale deflections. If the load on the circuit is nearly balanced there is a very simple method by which the sign of the wattmeter readings may be found. If either wattmeter is reading negatively it will be the one with the lesser deflection. Disconnect the potential coil of either wattmeter from *a* (see Fig. 5) and connect it to the remaining line. If the direction of the deflection reverses, the low-reading wattmeter was reading negatively. This method cannot be relied upon if the circuit is badly out of balance.

Polyphase Wattmeter.[1]—The two wattmeters used in the two-wattmeter method may be combined to form a polyphase wattmeter. The polyphase wattmeter is essentially two single-phase wattmeters, one placed above the other with their potential coils rigidly connected so as to act against a single spring to deflect a single pointer. Each element is connected as shown in Fig. 5. The torque acting on the spindle to deflect the pointer is the algebraic sum of the separate torques due to the two elements. Care must be taken in connecting such a wattmeter that the relative connections of the potential and current coils on the two

[1] LAWS, "Electrical Measurements," p. 333.

sides of the meter are symmetrical, otherwise the meter will indicate the algebraic difference instead of the algebraic sum of the torques due to its two elements.

Frequency Meters.[1]—The vibrating-reed frequency meter is a common type. It consists of a series of reeds, each one being tuned to vibrate at a particular frequency. The reeds are made of spring steel and located in the vicinity of an electromagnet which is excited from the mains of which the frequency is desired. The force causing the reeds to vibrate is very small and consequently causes only that reed to vibrate which has a natural period equal to that of the magnetic field. A high resistance is connected in series with the winding of the electromagnet in order that the meter may be connected directly across the mains. Taps are usually brought out of the large series resistance at a number of points in order that the amplitude of vibration may be adjusted. Since the meter is connected directly across the mains the required series resistance for high-voltage circuits is greater than for low-voltage circuits.

The resonating[2] type of frequency meter is a dynamometer having two moving elements fixed in space quadrature and subject to the influence of a fixed element. In series with one of the moving coils is a circuit tuned for resonance at a frequency below that of the circuit for which the meter is intended and in series with the other moving coil is another tuned circuit resonant at a frequency higher than that of the circuit whose frequency is to be measured. These two circuits are connected in parallel, the fixed coil carrying the vector sum of the moving coil currents. An increase in frequency causes the current in one of the tuned circuits to increase and that in the other to decrease and consequently a change in deflection results, while a decrease in frequency causes a reverse effect and consequently an opposite change in scale deflection.

A modification of this type[3] employs an iron vane for the moving element and the coils in space quadrature for the fixed element.

Still another type[4] consists of two induction motor elements

[1] LAWS, "Electrical Measurements," p. 546.

[2] W. H. PRATT and D. R. PRICE, "Resonant Circuit Frequency Indicator," *Trans. A. I. E. E.*, 1912, p. 1595.

[3] LAWS, "Electrical Measurements," p. 551.

[4] LAWS, "Electrical Measurements," p. 550.

which tend to drive a common rotor in opposite directions. The individual torques are a function of frequency and the net torque is also a function of frequency.

Oscillograph.[1]—The oscillograph is used in determining voltage and the current wave forms in alternating current circuits. To do this it must indicate instantaneous values and must, therefore, have a natural frequency several times the frequency of the circuit to be studied. High natural frequency requires very light moving parts. The moving element consists of two parallel strips of very thin phosphor-bronze which are kept in tension by means of a spring. These strips are supported by an ivory bridge in such a way that they lie in the same plane and are just far enough apart to insure insulation. This element is located in a strong field obtained by means of an electromagnet the direction of the field being such that it is at right angles with the element strips and parallel to the plane of the strips. If the strips are connected in series so that the current flows down through one and up through the other, one will be deflected forward and the other backward. By cementing a very small mirror to these strips at their center so that they are mechanically connected, the mirror will, for small currents, be deflected through an angle which is proportional to current.

By means of a suitable optical system a spot of light reflected from the small mirror may be caused to trace out the shape of the wave. The wave-form may be observed directly by using a rocking or rotating mirror to make the spot retrace every cycle or the wave-form may be photographed by mounting a sensitized film on a drum which is revolved at constant angular velocity and exposing it to the oscillating beam of light.

The wave-form having been determined it may be broken up into its components by a schedule analysis method using Fourier's series[2] or by some mechanical analyzer.[3]

Protection of Ammeters, Wattmeters and Voltmeters.—Ammeters and current coils of wattmeters are always placed in series with the circuit carrying the current to be measured. They

[1] L. T. ROBINSON, The Oscillograph and Its Uses, *Trans. A. I. E. E.*, 1905, p. 185.

LAWS, "Electrical Measurements," p. 629.

[2] LAWRENCE, "Principles of Alternating Currents," p. 89.

[3] DELLENBAUGH, "An Electromechanical Device," *Trans. A. I. E. E.*, 1921, p. 451.

should, therefore, be protected from excessive current due to accidental short-circuit of the line or to other cause by being kept short-circuited except when being read. All ammeters and wattmeter current coils used in the laboratory must be protected by short-circuit blocks provided for this purpose.

Voltmeters, potential circuits of wattmeters, and frequency meters, are arranged to be placed directly across the circuit and need no protection when the voltage range of their scale is greater than the voltage of the circuit to which they are attached, except when an inductive circuit is broken. When, however, a low range voltmeter is used to measure voltage in a part of a circuit which is supplied through resistance from a source of higher voltage, care must be taken to prevent injury to the voltmeter. If the circuit becomes accidentally opened between the points to which the voltmeter is attached, full line voltage will be put on the instrument, seriously injuring it if not actually burning it out. For this reason a voltmeter which is reading on its low voltage scale should be disconnected as soon as its reading has been recorded. A low-voltage scale must never be used without first making sure that the voltage of the part of the circuit across which the voltmeter is to be connected is within its range. The high-voltage scale should always be connected before trying the scale of lower range.

Measurement of Resistance by the Drop of Potential Method.—According to Ohm's Law, the current in any part of a circuit not containing a source of electromotive force but carrying a steady current is equal to the ratio of the voltage drop, through the part of the circuit considered, to the resistance.

$$I = \frac{V}{R}.$$

Transposing, this becomes $R = \frac{V}{I}$. If, therefore, the resistance of a circuit is desired, it may be measured by passing a known current through the circuit and measuring the potential difference between the terminals.

The ratio of this potential difference to the current will be the resistance. If the resistance to be measured is low, it will be necessary to connect another resistance in series with it to prevent excessive flow of current. In this case the voltmeter should, of

course, be connected across *only the resistance which is to be measured and not across the entire circuit.*

If the circuit is an *inductive* one, care must be taken to have the voltmeter *disconnected* when the circuit is made or broken.

Armature circuits and especially field circuits of motors and generators and transformer windings contain self-inductance.

When measuring small resistances, voltmeters with low-voltage scales are usually required. These scales, however, *must never be used* until the actual potential across the circuit has been measured on a scale having at least equal range to the voltage of the circuit which supplies the current. If the voltage drop is found to be within the range of the low-voltage scale this may be connected. *As soon as the voltmeter has been read, the low-voltage scale should be disconnected. Many voltmeters are burnt out by failure to take this very simple precaution.*

Rise in Temperature by Resistance Measurements.—The change in resistance of an electrical conductor with temperature gives a means of determining the increase in temperature in the windings of any piece of electrical apparatus. Thermometers give only the surface temperature. The resistance method gives the average temperature of the wire in the coil. What is desired is the highest or " hot spot " temperature in any part of the windings. See revised Standardization Rules of the American Institute of Electrical Engineers. When the resistance method is used a correction should be applied as recommended by the Standardization Rules of the A. I. E. E. It is customary for manufacturers to place resistance or thermal couples in large machines, where the hot spot is likely to occur in order that the temperature rise may be easily determined.

At ordinary temperatures, the resistance of metals increases a definite amount for each degree rise in temperature. Hence the temperature coefficient, which is the fractional increase in resistance per degree referred to the resistance at some initial temperature, varies with that initial temperature.

If then α_0 is the temperature coefficient at zero degrees centigrade,

$$\alpha_t = \frac{\alpha_0}{1+\alpha_0 t} \quad \ldots\ldots\ldots \quad (1)$$

where α_t is the temperature coefficient at a temperature of t degrees centigrade.

If R_0 is the resistance of any metal conductor at zero degrees centigrade and R_t is its resistance at the temperature t,

$$R_t = R_0(1+\alpha_0 t). \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The coefficient α_0 for annealed copper such as is used in windings is .00427.

Replacing α_0 by this value, equation (2) becomes

$$R_{t_1} = R_0(1+0.00427t_1). \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The resistance at any other temperature t_2 is

$$R_{t_2} = R_0(1+0.00427t_2). \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Combining equations (3) and (4),

$$\frac{R_{t_1}}{R_{t_2}} = \frac{1+0.00427t_1}{1+0.00427t_2}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$\frac{R_{t_2}-R_{t_1}}{R_{t_1}} = \frac{0.00427(t_2-t_1)}{1+0.00427t_1},$$

$$(t_2-t_1) = \left(\frac{R_{t_2}-R_{t_1}}{R_{t_1}}\right)\left(\frac{1+0.00427t_1}{0.00427}\right)$$

$$t_2-t_1 = \frac{R_{t_2}-R_{t_1}}{R_{t_1}}(234.5+t_1). \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Since the temperature rise is the fractional change in resistance divided by the coefficient at the initial temperature, equation (6) may be obtained directly from equation (1)

$$t_2-t_1 = \frac{R_{t_2}-R_{t_1}}{R_{t_1}} \div \frac{0.00427}{1+0.00427t_1} = \frac{R_{t_2}-R_{t_1}}{R_{t_1}\alpha_{t_1}}$$

or

$$\Delta_t = \frac{R_{t_2}-R_{t_1}}{R_{t_1}}(234.5+t_1), \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where Δ_t is the temperature rise in degrees centigrade.

Equation (7) is the most convenient form for calculating the temperature rise from resistance measurements, and is recommended in the Standardization Rules of the A. I. E. E.



TABLE OF MEAN TEMPERATURE COEFFICIENTS OF COPPER

Specific Resistance, Ohms per Meter-gram at 20° C.	Conductivity, Per Cent.	Temperature, 15° C.	Temperature, 20° C.	Temperature, 25° C.
0.1564	98	0.00393	0.00385	0.00378
0.1548	99	0.00397	0.00389	0.00382
0.1533	100	0.00401	0.00393	0.00385
0.1518	101	0.00405	0.00397	0.00389

Equation (7) gives the rise in temperature, Δ_t, above the initial temperature or the room temperature t_1, providing a machine has been idle for sufficient time immediately preceding the test to have attained room temperature.

The temperature-rise measurements in all pieces of electrical apparatus should be made as nearly as practicable at a room temperature of 25° to 40° C.

Resistance measurements for temperature rise must include only the resistance of the portion of the circuit in which the temperature rise is to be found. The resistance of nothing but copper should be included. If the resistance is to be measured by the drop of potential method the voltmeter leads must be placed directly on the terminals of the circuit. For example, when determining the temperature rise in an armature of a motor or generator, the voltmeter leads must be placed on the commutator bars that are beneath the brushes and not on the terminals of the armature circuit. Similarly in the case of a field, the voltmeter leads must be placed directly across the terminals of the field coils, inside of any rheostat or other resistance which may be in the circuit.

The resistance of the different paths through an armature will necessarily vary slightly. In order to eliminate any variation in resistance due to difference in path, the cold and hot resistances for temperature rise must be measured with the armature in exactly the same position. The ends (not the surface) of the commutator bars which are under a pair of brushes during the cold resistance measurement must be marked and the same bars brought under the same brushes for the hot resistance measurements. If exceptionally accurate results are to be obtained, the brushes should be lifted and separated from the commutator by

brass or copper strips which touch only one segment so that the current will enter the armature at definite points. The voltmeter leads should then be placed on the commutator segments through which the current enters and leaves the armature.

Resistances for temperature-rise measurements must always be taken with great care if reliable results are to be obtained. Great care should be taken to be sure the part in which the temperature rise is to be determined is at room temperature when its cold resistance is measured. Many inconsistent results are due to neglecting this precaution.

The hot temperature used for computing the temperature rise in any part of a machine under test should be the highest temperature reached immediately after shutting down the machine. Due to the decrease in cooling by convection when a machine is shut down, its surface temperature may continue to rise for several minutes. The highest temperature recorded will be more nearly the true hot spot temperature than the temperature recorded while the machine is running.

Temperature by Thermometer.—When a thermometer is used to measure the temperature of any part of a motor or generator, the bulb should be in contact with the part the temperature of which is to be measured. In order that the thermometer may give more nearly the temperature of the part which it touches, the thermometer bulb should be protected by a piece of putty or a small pad of cotton waste. The size of the pad of cotton waste or putty must not, however, be large enough to interfere with the natural cooling.

Measurement of Speed.—The simplest method of measuring the speed of any motor or generator is by means of one of the many forms of hand revolution counter which may be inserted in one of the conical center holes which will always be found in the ends of motor or generator shafts. With a little care perfectly satisfactory results may be obtained in this way.

When a number of readings of speed are required and particularly when any definite speed has to be maintained or produced, some form of direct reading tachometer is desirable.

There are many forms of tachometers on the market. Some depend upon some form of centrifugal device which acts through the gears on a pointer. Others count the number of revolutions for a given number of seconds, at the end of which time they indi-

cate the actual revolutions per minute. Some of these tachometers are very satisfactory, but they all require occasional calibration and are expensive.

One form of tachometer which is quite satisfactory consists of a small magneto generator driven from the shaft of the machine the speed of which is to be determined. If a voltmeter, preferably of high resistance, is attached to a magneto, its reading will be directly proportional to the speed. The voltmeter and magneto must be calibrated by keeping the voltmeter reading constant and measuring the speed by an ordinary revolution counter. Several sets of readings should be taken and averaged. If n is the speed in r.p.m. and V the corresponding voltmeter reading, $n=kV$ from which the constant k, in r.p.m. per volt, may be determined. If the range of speed over which the magneto is to be used is large, it should be calibrated at a number of different points. These points should cover the entire range of speed. If any sign of variation of the constant k is found, a plot should be made between speed and voltage and the speed corresponding to subsequent voltmeter readings taken from the plot. Even if k shows no sign of variation, a plot, which in this case will be a straight line will be convenient.

All magnetos as well as other forms of tachometers absorb some power. This, however, can usually but not always be neglected. When used on small machines a correction for the power absorbed often has to be applied. Small magnetos absorb about six to ten watts at 1000 r.p.m. The larger size require from two to three times this power to drive them.

Measurements of the Mechanical Output of a Motor.—The output of any motor is equal to the force exerted at the circumference of the pulley multiplied by the distance travelled in a minute by a point on the circumference. If r is the radius of the pulley in feet and n the revolutions made by it per minute, the output in horse-power will be

$$\frac{2\pi rnF}{33{,}000}$$

where F is the force in pounds exerted at the circumference of the pulley. The moment of the couple exerted by the pulley or the torque developed by the motor in pound-feet, T, is equal to the product Fr. If this torque is measured the output may easily be

calculated. In order to measure the torque, some form of friction or eddy-current brake is necessary. There are many forms of friction brake but these differ only in details.

One fairly satisfactory friction brake is shown in Fig. 6. *abc* is a friction band passing around the pulley. The turning moment or torque is measured by the difference of pull exerted at *a* by the spring balance *B* and at *c* by the weight *W* acting through the lever arm *cde*.

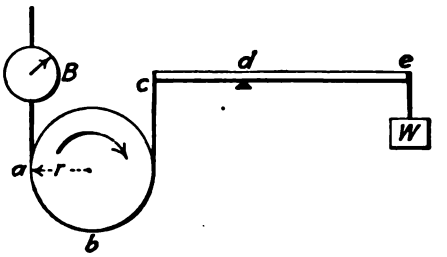


FIG. 6.

The load is varied by changing the tension of the band *abc* by altering the weight at *W*. The pulley must revolve in the direction of the arrow or towards the spring balance.

$$\text{Torque} = \left(W\frac{de}{cd} - B_0\right)r$$

where B_0 is the net balance reading.

Another convenient form is shown in Fig. 7.

A lever arm *ad* is supported at *b* on a knife edge. The band *aec* is fastened to the points *a* and *c* each at a distance from *b* equal to the radius of the pulley plus one-half the thickness of the band. The torque exerted by the pulley is balanced by the couple produced by the reaction of the pivot *b* and the upward pull of the spring balance at *d*. A knife edge must, of course, be used at *d* as well as at *b*.

$$\text{Torque} = B_0 \times bd.$$

If the distance *bd* is made one foot, the balance if graduated in pounds will read the torque directly in pound-feet. The load is varied by changing the tension of the brake band by raising or lowering the pivot *b*.

A third form which is satisfactory and somewhat less expensive than those given in Figs. 6 and 7, is shown in Fig. 8. In this

brake an arm *ad* has a wooden shoe, which fits the brake pulley, attached to one end. A piece of brake lining passes under the drum and is attached to a fixed hook at *e* and hooks on the end of a screw at *f*. A spring balance is attached to a knife edge at *a*. The load is varied by changing the tension of the belt by means of the screw *g*. The torque, $B_0 \times ab$, is the balance reading multiplied by the horizontal distance between the knife edge *a* and a vertical line through the center of the pulley.

In all forms of brake involving the use of an arm, the arm must be kept in a horizontal position provided, of course, the balance exerts its pull vertically.

The lever arm used in the brake shown in Fig. 6 must have a counter weight so that it may be balanced. This balancing

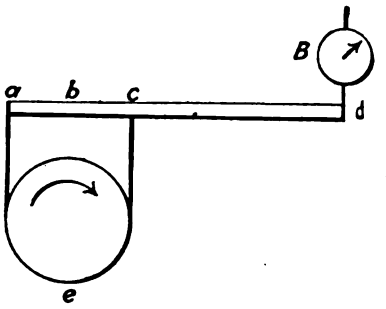


FIG. 7.

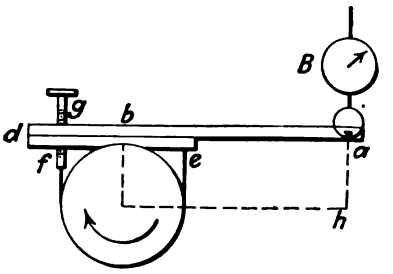


FIG. 8.

should be done with no weights in the pan at *W* and with the brake band hanging free from the pulley.

The lever arms in the other two forms of brakes need not be balanced. The unbalancing, however, must be such as to cause the end to which the spring balance is attached to be slightly too heavy.

All spring balances used in connection with brakes must be corrected not only for their zero errors but also for any pull exerted on them by the brake arm or band when the motor is not running.

The combined zero reading of the balance and brake for the brakes shown in Figs. 6 and 7 should be found by loosening the band until it hangs entirely free from the drum. The deflection of the balance under this condition will be its zero reading plus the zero reading due to brake. This zero reading must be subtracted from all subsequent readings.

The zero reading for the brake shown in Fig. 8 may be found in two different ways. For either, the brake band must hang entirely free from the pulley but must not be disconnected from the lever arm.

First method.—Turn the pulley or drum by hand very slowly until the brake shoe just slips. At this instant read the spring balance. Repeat, turning the pulley in the other direction. The mean of the two balance readings will be the zero reading of the brake.

Second method.—Lift the brake shoe and place a small piece of round metal rod between the shoe and drum directly over the center of the drum, and with the arm in a horizontal position read the spring balance. This will be the zero reading. If a round piece of metal is not available a round (not hexagonal) pencil may be used.

All forms of friction brake require special drums. Ordinary pulleys cannot be used as there is no means by which these can be kept cool. Unless artificially cooled, brake drums will become intensely hot and ruined. Moreover, heat will be transmitted through the shaft to the bearing and the bearing also injured.

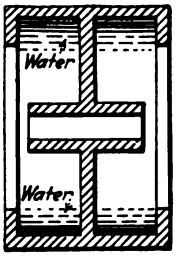


FIG. 9.

The usual means of cooling a brake drum is by keeping a film of water on the inside of its friction surface. This water, which keeps the drum cool by its evaporation, is retained by making the drum as indicated in cross section in Fig. 9.

Holes must be bored through the central flange near the circumference of the pulley to permit the passage of water from one side to the other.

The water will rapidly evaporate and must be replenished frequently. In replenishing it care must be taken not to wet the friction band. A large quantity of water should not be kept in the drum as it is apt to produce unbalancing.

A brake of the type illustrated in Fig. 8 with a 2-foot arm and a drum 12 inches in diameter with a shoe and brake band 4 inches wide will easily absorb 15 to 20 horse-power at a pulley speed of 1000 r.p.m.

The eddy-current brake, as the name implies, depends upon

the induction of eddy currents in metal disks or inductors which are rotated in magnetic fields. The eddy currents react on the impressed magnetic field giving a retarding torque, so the mechanical energy is converted into electrical energy and the latter finally converted into heat due to the I^2R loss in the disk or conductor.

One form of this brake is illustrated in Fig. 10. This brake is air cooled and operates satisfactorily on motors up to 10 horsepower rating.

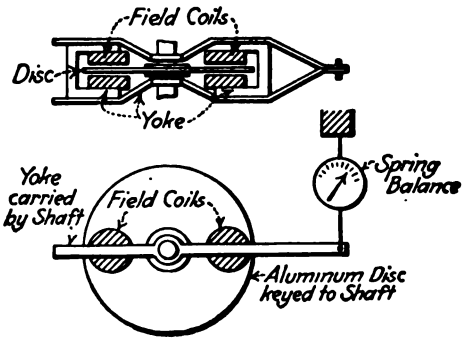


FIG. 10.

The electromagnets are excited with direct current and the load is varied by means of a rheostat in their circuit. The zero reading of the balance is obtained by revolving the disk slowly by hand first in one direction and then in the other and taking the mean of the two balance readings thus obtained. Since certain windage losses due to the eddy current disk are not indicated by the balance it is necessary to correct the output for these losses. Correction curves showing disk windage should be obtained as a function of speed.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. I, chap. II.

DAWES, "Electrical Engineering," vol. I, p. 122 and vol. II, chap. III.

CHAPTER II

THE CALCULATION OF INSTRUMENT RANGES

THE selection of the proper ranges of instruments for any particular test is of great importance. If, for example, any meter selected is of too low range, it is likely to be burned out or to have its pointer bent and conversely, if it is of too great range the accuracy of the readings is reduced. Ammeters should be selected which have a full-scale deflection slightly in excess of the maximum expected reading. This is to allow for a momentary overload. Voltmeters should be of the next range higher than the voltage of the circuit being measured, except when a variable voltage run is made when a multiple range meter may well be employed.

In order that the full-load input and losses of various machines may be estimated a table of losses (see end of chapter) has been prepared. This gives the average full-load efficiency, full-load armature copper loss, full-load stray-power loss and full-load field loss for several sizes of direct-current motors and generators of normal design. The efficiency and losses of any intermediate size may be obtained by interpolation. The efficiency of any particular machine may differ materially from the values given which of course are average. The largest variations will occur in the percentage distribution of losses, where a variation of 50 per cent. would not be unusual.

The losses in alternating-current machinery may be assumed to be approximately the same as those of direct-current machines without producing very great errors in calculation of instrument sizes. The average efficiencies, copper losses, core losses, and exciting currents in per cent. of full-load current for 60-cycle transformers are given lower in the table. The percentage exciting currents for 25-cycle transformers may be taken as four times the values given for 60 cycles.

The following illustrations will serve to explain the foregoing:

(*a*) Calculate the necessary ranges of instruments to measure the input and output of a 5 horse-power shunt motor, rated at 230 volts and 1100 r.p.m. equipped with a Prony brake, having a 2-foot arm.

Referring to the table of losses previously mentioned we find that machines of this size average to have an efficiency of 80 per cent. The input at full load then equals

$$\frac{\text{output}}{\text{efficiency}} = \frac{P_0}{\eta} = \frac{5 \times 746}{0.80} = 4670 \text{ watts},$$

and for 25 per cent. overload the input is $4670 \times 1\frac{1}{4} = 5840$ approximately. Since power is supplied at 230 volts, the current

$$I = \frac{P}{V} = \frac{5840}{230} = 25.4 \text{ amperes}.$$

This would require an ammeter of at least 0–30 amperes range. In order to measure voltage an instrument of 0–300 volts range would probably be selected. The speed would probably be taken with a Veeder counter or some form of direct-reading tachometer. The torque would be measured by means of a spring balance at the end of a 2-foot arm. For 25 per cent. overload this would be

$$T = \frac{33000 \times \text{h.p.}}{2\pi n} = \frac{33000 \times 5 \times 1\frac{1}{4}}{2\pi \times 1100} = 29.9 \text{ lb-ft}.$$

$Fl = T$. $F = 14.95$ pounds. Allowing for zero reading at least a 20-pound balance should be used.

In case the field current is desired, it may be calculated from the percentage field loss. At full-load this averages 4 per cent. of input

$$P_f = \frac{5 \times 746 \times 0.04}{0.80} = 187 \text{ watts},$$

which for a shunt machine would be the same for all loads. The field current equals the power lost divided by the voltage

$$I_f = \frac{P_f}{V_t} = \frac{187}{230} = 0.812 \text{ ampere},$$

and a meter of 0–1 ampere range could be used.

To determine the actual armature copper loss the armature resistance must be measured. This is generally done by the drop of potential method, measuring the voltage drop across the armature when full-load current flows. Under this condition the

same copper loss is obtained as at full-load which averages 5.5 per cent. of input

$$P_a = \frac{5 \times 746 \times 0.055}{0.80} = 257 \text{ watts.}$$

The voltage drop across the armature when this power is lost is

$$V_a = \frac{P_a}{I_a} = \frac{257}{19} = 13.5 \text{ volts,}$$

assuming name-plate current equal to I_a. A low-range meter of 0–15 volts would do here. Generally a multiple scale instrument is selected having a low-range scale suitable for the measurement of armature resistance drop and a high-range scale for measurement of line voltage in the load run, since the two voltages need not be measured at the same time. The ammeter may be the one used for measuring the load current.

In case the stray power of a machine is to be determined it is necessary to make a no-load run. The power taken by an armature at no load is practically equal to the stray power except for the negligible copper loss. The average stray power for a machine of this size is 10.5 per cent of full-load input.

$$P_{SP} = \frac{5 \times 746 \times 0.105}{0.80} = 490 \text{ watts.}$$

Since this is supplied at rated voltage the no-load armature current is

$$I_{a_0} = \frac{P_{SP}}{V_t} = \frac{490}{230} = 2.03 \text{ amperes,}$$

for which a 0–3 ampere instrument would probably be satisfactory.

(*b*) For another illustrative example consider measurements on resistance, inductance and capacitance in series and in parallel. Suppose a resistance of 10 ohms, an inductive reactance of 50 ohms at 60 cycles and an adjustable capacitance of 80 microfarads are connected in series on a 60-cycle, 110-volt circuit and the capacitance adjusted for resonance. If it is desired to measure the line current and the voltage drops across the various parts of the circuit a calculated estimation of ranges for these instruments will be necessary.

For resonance

$$I = \frac{V}{R} = \frac{110}{10} = 11 \text{ amperes.}$$

$$V_R = IR = 11 \times 10 = 110 \text{ volts.}$$

$$V_L = V_C = IX_L = 11 \times 50 = 550 \text{ volts.}$$

Instruments of sufficient range to make the above measurements should be selected, and these will be large enough for any conditions out of resonance.

Consider the same units connected in parallel across a 110-volt circuit and adjusted for resonance. The line current equals

$$I=\frac{V}{R}=\frac{110}{10}=11 \text{ amperes.}$$

$$I_R=\frac{V}{R}=\frac{110}{10}=11 \text{ amperes.}$$

$$I_L=I_C=\frac{V}{X_L}=\frac{110}{50}=2.2 \text{ amperes.}$$

If L is decreased or C increased the current in either branch will increase, increasing the line current, so the degree of departure from resonance should be considered in selecting meters. The voltmeter is, of course, simply one capable of measuring line voltage.

In case the resistance was removed when at the condition of parallel resonance the line current would be very small supplying simply the small effective-resistance loss and core loss of the inductance and the leakage and dielectric-hysteresis loss of the condenser. The magnitude of these is dependent upon the quality of the iron and of the dielectric.

(*c*) As a final example, consider a 5 kv-a. 2200/220-volt, 60-cycle single-phase transformer. It is desired to measure the ohmic resistance of high- and low-tension windings as well as to determine the core and copper losses from no-load runs.

The full-load currents for high- and low-tension sides are

$$I_H=\frac{5000}{2200}=2.27 \text{ amperes,} \quad I_L=\frac{5000}{220}=22.7 \text{ amperes.}$$

From the table of losses we find that the copper loss is 90 watts. This may be assumed to be equally divided between high- and low-tension windings. If we divide the copper loss in any winding by full-load current we obtain the necessary voltage to make full-load current flow. The resistance drops due to full-load high- and low-tension currents are respectively

$$V_H=\frac{45}{2.27}=19.8 \text{ volts,} \qquad V_L=\frac{45}{22.7}=1.98 \text{ volts.}$$

An ammeter with 3- and 30-ampere shunts and a low-range voltmeter with 3- and 30-volt ranges would be suitable here.

The core loss is obtained by impressing rated frequency and voltage on the transformer. The voltmeter is thus determined. The ammeter may be obtained knowing that the exciting current for a transformer of this size is approximately 3 per cent. of full-load current. Suppose we are impressing voltage on the low-tension side, the current would be $I_n = 22.7 \times .03 = 0.68$ ampere. This, then, determines the ranges of ammeter, voltmeter and wattmeter.

The full-load copper losses may be obtained by short-circuiting the low-tension winding and impressing sufficient voltage on the high-tension winding to cause rated current (2.27 amperes) to flow. The voltage required will be approximately 5 per cent. of rated voltage $= .05 \times 2200 = 110$ volts. This determines the ranges of ammeter, voltmeter and wattmeter.

(*d*) The field loss of an alternator may be computed approximately, in the same manner as that for a direct-current shunt motor. The field current is then obtained by dividing this loss by the d-c. excitation voltage which is usually different from the a-c. voltage.

TABLES OF LOSSES IN MOTORS, GENERATORS AND TRANSFORMERS

Shunt and Series Motors

Efficiency and Distribution of Losses at Full Load

Rating Horse-power.	Efficiency, Per Cent.	Total Losses, Watts.	Armature I^2R. Loss, Per Cent.	Stray-power Loss, Per Cent.	Field Loss, Per Cent.
1	74.5	250	6.0	14.5	5.0
2	76.5	450	6.0	13.0	4.5
5	80.0	940	5.5	10.5	4.0
10	84.5	1370	5.0	7.0	3.5
15	86.5	1760	5.0	5.5	3.0
25	89.0	2300	4.2	4.0	2.8
50	90.5	3950	3.7	3.5	2.3
100	91.5	6900	3.5	2.8	2.2

SHUNT AND COMPOUND GENERATORS

Efficiency and Distribution of Losses at Full Load

Rating Kilowatts.	Efficiency, Per Cent.	Armature I^2R, Loss, Per Cent.	Stray-power, Loss, Per Cent.	Shunt-field, Loss, Per Cent.
1	74.0	6.0	15.0	5.0
2	77.0	5.8	12.7	4.5
5	81.5	5.5	9.3	3.7
10	85.5	5.0	6.5	3.0
15	87.5	4.8	5.1	2.6
25	89.5	4.2	3.9	2.4
50	91.0	3.6	3.2	2.2
100	92.0	3.2	2.8	2.0

The resistance of the series field of a compound generator or motor is approximately one-eighth to one-quarter the resistance of the armature.

TRANSFORMERS

60*-cycle

Rating Kilowatts.	Efficiency, 100 Per Cent., p.f.	Copper Loss, Watts.	Core Loss, Watts.	Exciting Current, Per Cent. of Load Current.*
2	96.0	40	40	6.0
5	96.8	90	70	3.0
7.5	97.2	115	95	2.3
10	97.5	140	110	2.0
25	98.0	290	210	1.2
50	98.3	475	375	0.8
100	98.4	900	700	0.4

* Assume the exciting current of 25-cycle transformers is four times that of 60-cycle transformers.

CHAPTER III

SUGGESTIONS FOR THE WRITING OF REPORTS

THE best preparation for laboratory work is the writing of a preliminary report in which the student explains in his own words just exactly what he proposes to do. It is advisable to look up several references first and then write down the method of test without referring to books. The following is the suggested content of such a report:

1. Description of test.
2. Diagram of all connections, including instruments, rheostats and starting boxes, where used.
3. Readings to be taken and the conditions under which they are to be taken.
4. Method of loading, or adjusting to desired electrical conditions of test.
5. Calculation from name-plate data of necessary instrument ranges.

If the above is required the student should always have a clear idea of what is to be done.

The following outline is suggested as a final report on the laboratory work:

1. Tabulation of required results and calculations followed by sample calculations showing formulas used and substitutions made for one point on each different kind of curve. This to be followed by a tabulation of all calculated data.
2. Curve sheets.
   (*a*) Zero reference axis of each curve on plot.
   (*b*) All curves on the same sheet unless they cause undue interference.
   (*c*) Decimal scales are to be used.

(*d*) Name-plate data and serial number of apparatus tested to be placed on curve sheet.

3. Discussion of results, reasons for shapes of all curves and conclusions. Consider any errors which may be involved in the measurements and also any assumptions made which may lead to error.
4. Original uncopied data, columns headed with:
   (*a*) Instrument numbers.
   (*b*) Zero readings of above.
   (*c*) In case of multiple-range instruments, the ranges used.
   (*d*) In case of multiple-scale instruments, the scale which was used.
   (*e*) Units in which meters read.
   (*f*) Instrument resistances.

Reports should be prepared neatly and arranged in such a manner that anyone unfamiliar with the methods used in the laboratory could ascertain just what was done, and under just what conditions. Reports prepared in this manner would be valuable for future reference, both for the data contained and as an example of a process of analysis.

The statements made in procedure should state exactly conditions under which measurements were made and leave no possible chance for doubt. To illustrate, in connection with the load run on a shunt motor, do not simply say, "Measure input and output" since these are not measured directly, but rather say, "Measure line current and terminal voltage in order to determine input, and measure speed and pull at the end of a Prony brake arm in order to determine output."

In the discussion of results, the statement should be in the form of an analysis. Given the conditions under which a piece of apparatus operates, determine what is varied and how. Next analyze how this affects other factors involved and gives rise to the characteristic curves. This form of discussion enables the student to trace from cause to result and will develop ability for clear thinking, which should be a valuable asset in any field of endeavor.

The Number of Figures to Be Retained in Data.—The number of figures to be retained in data should always be determined by the reliability of the measurements. The retention of unnecessary

figures is not only misleading, but absolutely misrepresents the accuracy of any piece of work. A good general rule for ordinary engineering work is to reject all figures in final results beyond the first place in which variation occurs. For example, suppose a current of 50 amperes is to be read on an ammeter having one hundred divisions, each division representing one-half an ampere. If the conditions of the circuit are sufficiently constant to permit reading tenths of division, the figure in the first place after the decimal point should be retained. If this happens to be zero it should not be omitted. The current in this case should be written 50.0 and not simply 50. If the conditions of the circuit were so variable that the ammeter could not be read closer than 5 amperes, the current should be recorded only to the nearest 5 amperes. In the mean of a considerable number of single observations, one more figure should always be retained than is kept in the single observation.

If two or more quantities having different accuracies are multiplied or divided, the number of figures retained in the result should be determined by the least accurate of two quantities. For example: If the input to a motor is given as 51 amperes at 110.3 volts, the calculated input in watts should be written 56,000 watts and not 56,253 watts. If the first figure rejected is five or greater, one should be added to the figure next preceding.

Slide Rule.—The ordinary 10-inch slide rule, if used with care, ought to yield results, in the case of simple computations, which are reliable to about one-half of 1 per cent. Used carelessly, however, or without discretion, the slide rule will give results which are *absolutely* worthless.

When an accuracy greater than one-half of 1 per cent. is desired, logarithms must be resorted to. Even when this accuracy is desired, the slide rule may still be used for parts of the computation as, for instance, correction terms, where often an error of 3 or 4 per cent. or sometimes even 10 per cent. will scarcely affect the result.

Slide rule computations are accurate enough for most engineering work, but efficiencies which are calculated from direct measurements of the losses in any piece of high-efficiency apparatus will usually warrant the use of logarithms. Even in these cases the slide rule is usually sufficiently accurate for computing the losses.

If P_t is the total loss in a transformer under any assumed output, the efficiency will be

$$\frac{\text{Output}}{\text{Output}+P_t}.$$

If P_t is 4 per cent. of the output the numerical value of the efficiency will be

$$\frac{100.0}{100.0+4.0}=\frac{100.0}{104.0}.$$

An error of one part in forty or $2\frac{1}{2}$ per cent. in the losses will affect the efficiency only by about 0.1 of 1 per cent. In a case of this kind, the accuracy of the slide rule is amply sufficient for the calculation of the losses, but logarithms should be used in the computation of the ratio of output to the input.

Plots.—The most convenient method of showing the performance of any piece of electrical apparatus is by means of a plot of its characteristic curves. Usually, all of the characteristic curves of any motor or generator can be put on a single sheet, but judgment must always be used in arranging the curves in order to prevent confusion. The intersection of two or more curves which have nearly the same slope should be avoided. Students should consult some of the trade bulletins in order to familiarize themselves with the customary method of arranging plots of the characteristic curves of electrical apparatus.

Scales.—A good general rule to be followed in selecting a scale for a plot is to use a scale which will permit plotting the last figure retained in the data, to estimated tenths or fifths of the smallest divisions on the plotting paper. For example: The voltage of a 110-volt circuit would probably be measured by a voltmeter with 150 divisions, each representing one volt. This voltage would be read to one-tenth of a volt. In plotting these data, the tenths volts would be plotted by estimating tenths of volts between the smallest divisions on the plotting paper. The above rule cannot be rigorously followed, but it should not be violated without good cause as, for instance, in order to improve the slope of a curve or to better the arrangement of the curves on a plot.

Nothing but decimal scales should be used. Scales divided into quarters, thirds, sixths, etc., must be avoided. They are extremely inconvenient in plotting and are very difficult to read.

In Figs. 11 and 12 are given some examples of both good and bad scales. The zero points of all scales used on any plot should be placed at the origin of the axes of coordinates.

The numbers for the scales on any plot and what these numbers represent should be placed along the margins. Plotted lines must be marked in such a way that they can easily be identified. Sufficient data should also be placed in lower right-hand corner of a plot to identify completely the apparatus for which the plot is made. In case of a motor or generator these data should include the name of the manufacturer, the type, the rating and the serial number of the machine.

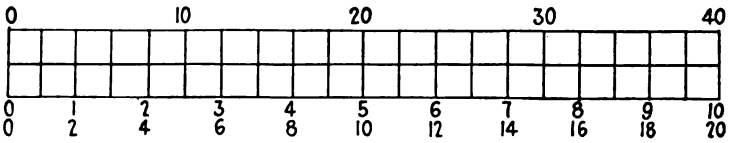


FIG. 11.—Good scales.

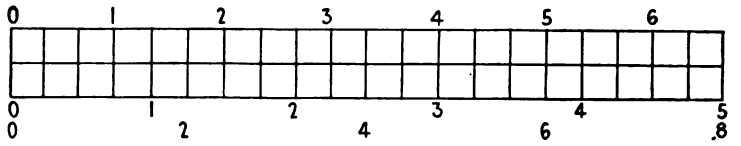


FIG. 12.—Bad scales.

Due to errors of observation and to the impossibility of maintaining perfectly constant conditions during any test, plotted points will very seldom lie exactly along a smooth line. Smooth lines, however, should always be drawn. These lines should be placed so as to best represent the plotted points, and should be so drawn that the points fall alternately on either side of the curve.

Lines should be sketched in lightly with a pencil and then, after their best shape and position have been determined, they should be gone over with ink, using French curves. The plotted points should not be erased. When there are several curves on a sheet, the points belonging to any one curve must be easily distinguishable.

1

WHEATSTONE BRIDGE

A very convenient and also a very accurate method of measureing ordinary resistances is by means of a simple arrangement called the Wheatstone bridge. Fig. 13 is diagrammatically a sketch of this instrument.

E is a battery of two or three dry cells, R_M and R_N are the resistances of the branches ac and cb respectively and are called

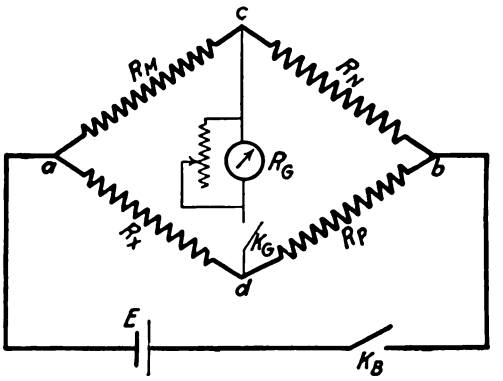


FIG. 13.

the ratio arms. R_P is the resistance of branch db, called the balance arm and R_X is the resistance of the branch ad which is unknown. R_G represents the galvanometer and also its resistance in ohms. If R_M and R_N have fixed values and R_P is varied, there is some value of R_P for which the galvanometer current will be zero. This will be indicated by the galvanometer showing no deflection when keys K_B and K_G are closed in the order named. If there is no galvanometer current the potentials at points c and d must be the same. Hence the resistance drops from a to c and a to d are equal. That is

$$I_M R_M = I_X R_X. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Likewise the drop from c to b will be equal to the drop from d to b or

$$I_N R_N = I_P R_P. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

But since there is no galvanometer current

$$I_M = I_N \text{ and } I_X = I_P.$$

Dividing (1) by (2) gives

$$\frac{R_M}{R_N} = \frac{R_X}{R_P} \text{ or } R_X = R_P \frac{R_M}{R_N}. \quad . \quad . \quad . \quad . \quad . \quad (3)$$

It is seen that, with a fixed value of the ratio of R_M to R_N, it is possible to so adjust R_P that the galvanometer deflection disappears, which shows that there is no galvanometer current.

A convenient form of the bridge and one which is very commonly used in the laboratory has ratio arms R_M and R_N which contain coils of 1, 10, 100 and 1000 ohms. In addition there is a 10,000-ohm coil which may be added to either R_M or R_N by connecting c to the proper binding post.

The arm R_P contains many coils of such magnitudes that any resistance from 1 ohm to 10,000 ohms may be inserted in 1-ohm steps.

Besides the bridge box the other necessary pieces of apparatus are the battery (usually two or three cells), the keys K_B and K_G, the galvanometer, a shunt for the galvanometer, and a commutator (not shown) for reversing the current.

Keys K_B and K_G are usually combined to form what is called a bridge key, which when depressed throws in first the battery and then the galvanometer. This is to eliminate the effects of inductance and capacity in the bridge coils and in the unknown resistance. In manipulating this key care should be taken not to touch the metal work, thus avoiding the chance of leakage to the galvanometer and also thermoelectric effects. A commutator is used to reverse the battery current and so to eliminate the effects of thermo-electromotive forces.

The galvanometer should be one which is unaffected by variations of the local field, that is, either a shielded Thomson or a d'Arsonval. The former is in certain cases much to be preferred,

for suppose the bridge arms between the galvanometer terminals are of moderate resistance and that a d'Arsonval instrument is employed. Upon the establishment of the current, the coil begins to move and sets up an electromotive force in the circuit and the motion will be damped, so that instead of a sharp, decided movement of the spot of light on the screen, the deflection will take place so deliberately that the key has to be kept depressed some time before the deflection is completed. This is not so if a proper Thomson galvanometer is used; however, this type of instrument, to be of practical use nowadays, must be shielded with concentric iron shields, so that it will not be influenced by extraneous magnetic disturbances.

A shunt or by-pass for the galvanometer current is placed across the galvanometer terminals. This is used during preliminary adjustments to protect that instrument against currents of abnormal strength. By means of a movable arm the value of the shunt resistance may be altered so that as the adjustment of the bridge nears perfection, and in consequence the galvanometer deflections become small, more of the current can be sent through the instrument by increasing the shunt resistance. During the final adjustment, when full sensitiveness is desired, the movable arm should be turned so far to one side that it opens the shunt and allows the entire current to flow through the galvanometer. The various positions of the movable arm are usually so arranged that either 0.001, 0.01, 0.1, or the full current may be sent through the galvanometer. *Always begin measurements with the galvanometer heavily shunted, so that there may be no violent deflection of the instrument.*

To make a measurement, the coil of unknown resistance is inserted as indicated in Fig. 13. The various connections there shown are to be made. See that all connections are perfect, and that all binding posts are screwed up tightly, but without undue force. Have all plugs firmly inserted and the galvanometer heavily shunted. Obtain first a rough idea of the magnitude of R_X as follows: Make $R_M = R_N$; draw the 1-ohm plug in R_P; depress the key with care, being ready to release it immediately should the deflection of the galvanometer be violent. The deflection will be, say, toward the left. Note this, plug up the 1-ohm coil, and draw the 5000-ohm or other high plug; proceed as before. The deflection may be, say, toward the right; then you know that R_P and

consequently R_X is between 1 ohm and 5000 ohms. If one deflection is greater than the other, you know that the proper value of R_P is nearer the resistance which gives the smaller deflection. Next try 10 ohms in R_P. Suppose the deflection to still be towards the left; you know that the proper value of R_P is between 10 ohms and 5000 ohms. Proceed in this manner, always narrowing the limits between which the right value of R_P must be located. Having gotten an apparent balance, increase the galvanometer shunt resistance and proceed to a better approximation. Suppose that the bridge finally balances with $R_P = 25+$ ohms, 25 ohms being too small and 26 ohms too large; then R_X is between 25 and 26 ohms. It is obvious that the determination of R_X is good to only about 2 or 3 per cent. Suppose that R_X is desired to 0.1 per cent.; then as the smallest coil in R_P is 1 ohm, R_P must be between 2500 and 2600 ohms in order that the smallest step may represent most nearly the desired precision. Accordingly make R_P 2500 ohms *and alter the balance arms* R_M *and* R_N *to correspond.*

$$R_X = 25+$$

$$R_P = 2500,$$

$$\frac{R_M}{R_N} = \frac{R_X}{R_P} = \frac{25}{2500} = \frac{10}{1000}.$$

Make $R_M = 10$ ohms and $R_N = 1000$ ohms; gradually increase R_P from 2500 ohms until exact balance is obtained, with all shunts removed; then

$$R_X = \frac{R_M}{R_N} R_P.$$

In the above it has been supposed that with $R_M = R_N$ the deflections with $R_P = 1$ ohm and $R_P = 5000$ ohms were one to the right, the other to the left. If they had been both to the right and the one with $R_P = 1$ ohm of the lesser magnitude, then the proper value of R_P would have been below 1 ohm and R_X less than 1 ohm. In such a case proceed at once to change the ratio of R_M and R_N so that 1 ohm in R_P balances, say, 0.01 ohm in R_X. In other words, make $\frac{R_M}{R_N} = \frac{1}{100}$, and proceed as before with the adjustment of R_P.

If R_P should be greater than 5000 ohms, the proper procedure may be decided upon from the above discussion. This is called the Null method.

As a final precaution, go over all connections to see that they are tight and that all the plugs are firmly in place; then make the final balancing and record the values of R_M, R_N, and R_P. Now reverse the battery current and test again, and if necessary rebalance; this is to eliminate thermo-currents. Use the average result for R_P in calculating R_X.

Referring again to the example just discussed, with $R_M = R_N$, R_P was between 25 and 26 ohms and R_X could be determined to only 2 or 3 per cent. Now suppose that with $R_P = 25$ ohms the galvanometer deflects from its zero position thirteen divisions to the left, and with $R_P = 26$ ohms nine divisions to the right; then we may interpolate, for a change of 1 ohm in R_P causes the spot of light to vary twenty-two divisions, and the proper value of R_P for exact balance will be 25 ohms $+\frac{13}{22}$ ohm, or 25.59 ohms. As the readings of the deflections cannot generally be taken with great accuracy, 25.6 ohms would be the value of R_P to be accepted. It is obvious that if this procedure be followed R_X may be determined to $\frac{1}{2}$ per cent. without changing the ratio from $R_M = R_N$. If the ratio be changed, then we may still further increase the precision. This method is used to gain precision when R_X is so small that R_P must be of a small value. For this method the battery must remain perfectly constant. This method is slower in its application than the Null method, and the arms of the bridge are much more likely to be overheated.

Procedure.—Employing the Null method described above measure the resistance of the potential coil of a wattmeter. Also measure the resistance of a multiplier. Using the deflection method measure the resistance of the current coil of the wattmeter and after this measure the lead resistance. Make each measurement for battery current in both directions.

Results Required.—

a. Resistance of current coil of wattmeter corrected for lead resistances.

b. Resistance of potential coil of wattmeter.

c. Resistance of multiplier.

d. Multiplying power of multiplier when used with above wattmeter.

e. Per cent. precision of above measurements.

f. In what way do contact resistances affect the precision of the results?

LAWS, "Electrical Measurements," p. 182.
FARMER, "Electrical Measurements in Practice," p. 124.
KARAPETOFF, "Experimental Electrical Engineering," vol. I, p. 13.
DAWES, "Electrical Engineering," vol. I, p. 141.

2

DIRECT-CURRENT POTENTIOMETER

The measurements of current, voltage and power which are necessary in engineering work are effected by means of portable indicating instruments. Development has brought these appliances to a high degree of perfection, but it must be kept in mind that even in the best of them there are possible sources of error so that, if one is to be certain of his results, it is necessary to calibrate the indicating instruments which he uses, by some method which is free from these sources of error and which is capable of giving more accurate results than can be obtained by indicating instruments. After an instrument has been calibrated, corrections may be applied to its readings and accurate results obtained.

In nearly all portable electrical instruments the torque exerted on a movable coil or on a soft iron needle is balanced by a spring. In the most commonly used direct-current instruments the torque is due to the action of a coil, carrying a current, which is placed in the field of a permanent magnet. The magnets may deteriorate and if the spring be deformed in any way its constant may be changed. There are other possible sources of error. It is seen that it is necessary to have some method for measuring the electrical quantities which will not be dependent on the action of springs, permanent magnets, etc.

The direct-current potentiometer, together with its accessories, enables us to calibrate direct-current ammeters and voltmeters as well as those meters for alternating-current work which are based upon the electrodynamometer principle. Soft-iron ammeters and voltmeters may be dealt with by the use of hot-wire transfer instruments.

As commonly constructed a potentiometer is capable of directly measuring potential differences of from 0 up to 1.6 volts. There are various designs of the instrument, all based on the same funda-

mental principle. The Leeds and Northrup instrument will be described later.

The potentiometer is based on Poggendorff's [1] method for determining the value of a potential difference by comparing it with a known electromotive force.

The connections for Poggendorff's method are shown in Fig. 14. E and E_S are the electromotive forces of cells E and E_S respectively. R_1 and R_2 are two variable resistances connected in series. K is a key which is normally open and G is a suitable galvanometer. The circuit of battery E is closed through the resistance R_1+R_2 across

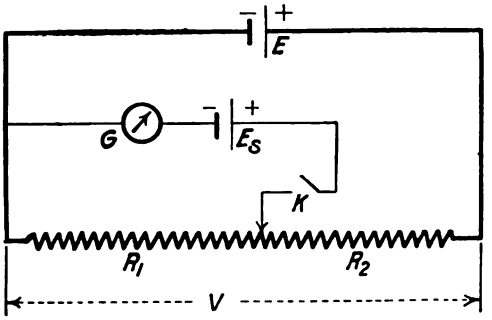


FIG. 14.

which there is established a difference of potential V. When K is open

$$I_1=I_2=\frac{V}{R_1+R_2}, \quad \ldots\ldots\ldots \quad (1)$$

and the potential difference V_1 between the ends of R_1 will be

$$V_1=V\times\frac{R_1}{R_1+R_2}. \quad \ldots\ldots\ldots \quad (2)$$

This may be varied by varying R_1 or R_2 or both. The battery E_S is inserted so that its electromotive force opposes the potential difference due to the passage of the current through R_1. If now by varying R_1 or R_2 this latter potential difference is made equal to E_S no current will flow in the galvanometer circuit and the galvanometer will not deflect.

Hence at balance

$$E_S=V\times\frac{R_1}{R_1+R_2}. \quad \ldots\ldots\ldots \quad (3)$$

If now, R_1+R_2 be so large that the current in the battery E is small, the internal voltage drop IR_E in the battery may be assumed to be negligible. Hence very closely

$$\frac{E_S}{E}=\frac{R_1}{R_1+R_2}, \quad \ldots\ldots\ldots \quad (4)$$

and

$$E=E_S\frac{R_1+R_2}{R_1}. \quad \ldots\ldots\ldots \quad (4)$$

It should be noted that at balance $I_1=I_2$ and $I_1R_1=E_S$ or

$$I_1=\frac{E_S}{R_1}. \quad \ldots\ldots\ldots \quad (5)$$

It will be noticed that current flows in E_S only when K is depressed and when the adjustment is perfect no current flows. This is of importance because it allows a standard cell to be used at E_S without danger of altering its electromotive force by polarization. Standard cells are designed to have perfectly definite electromotive forces. No appreciable current can be drawn from such a cell without lowering its electromotive force due to polarization.

The electromotive force E_S may be replaced by a potential drop, provided it be obtained from a source which is entirely independent of E. This is done in the connections shown in Fig. 15. If the resistances are so adjusted that the galvanometer is not deflected when K is depressed the drop in R_1' is equal to the potential difference V_3 or

$$I_1'R_1'=V_3=I_3R_3. \quad \ldots\ldots\ldots \quad (6)$$

In the potentiometer the connections shown in Figs. 14 and 15 are both utilized; the first when the current from E is adjusted to a standard value; the second when, after having adjusted the current from E, an unknown potential difference is measured. From equation (6) it is seen that if I_1' is always adjusted to some definite value, for instance 0.02 ampere, then

$$V_3=0.02\times R_1'.$$

If the current be maintained at 0.02 ampere and if R_1' and R_2' are made up of a series of coils all having the same resistance, every

position of the connection b will correspond to a definite drop in voltage between a and b, and it then becomes possible to mark the resistances so that one can read directly from the scale the voltage drop produced between a and the adjustable point b by the current of 0.02 ampere. This is the fundamental principle of all potentiometers.

In the Leeds and Northrup Low-resistance Potentiometer [2] a battery W (in Fig. 16) is connected in the circuit $WRKOADBW$. This corresponds to the circuit of E in Figs. 14 and 15. The principal elements in this circuit are the balancing rheostat R, by which

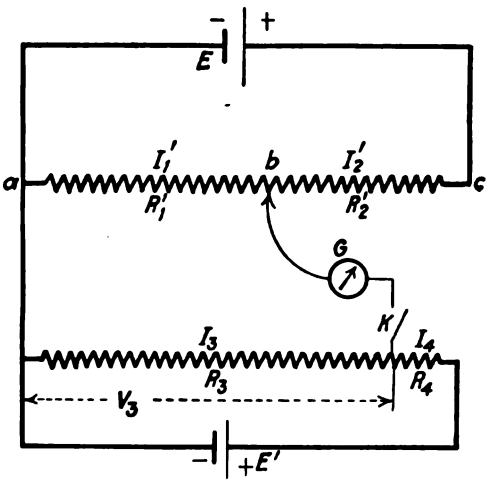


FIG. 15.

the potentiometer current is adjusted to the standard value of 0.02 ampere, the standard-cell rheostat T, the coarse-adjustment arrangement AD consisting of fifteen 5-ohm coils, and the fine-adjustment wire DB.

The standard-cell rheostat from T to A, in series with 10 of the 5-ohm coils, corresponds to R_1 in Fig. 14. The function of the standard-cell rheostat will be explained later. When the double-throw switch U is thrown to the position marked STD. CELL, the galvanometer, the standard-cell and the key R_1, are shunted around the resistance TAF just as the galvanometer, the cell E_S, and the key K in Fig. 14 are shunted around R_1. When the double-throw switch U is thrown to the position marked e.m.f. the galvanometer is in the position shown in Fig. 15. Under this con-

dition the electromotive force marked E.M.F. in the lower part of Fig. 16 corresponds to V_3 in Fig. 15. The resistance of the 5-ohm coils and of the slide wire which are included between the adjustable contacts M and M' correspond to R_1' in Fig. 15.

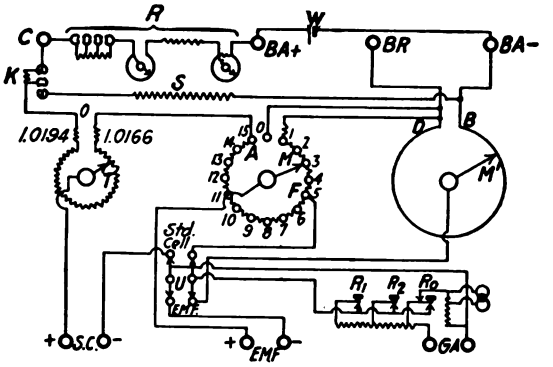


FIG. 16.

Referring to Fig. 17, the rheostat in the upper left-hand corner is T, next to it on the right is AD and the cylinder to the right of this is DB. The scale in front is graduated in number of turns, and the circumference of the cylinder is divided into fractions of a



FIG. 17.

turn. On the end is R, divided in two parts, the one near the back being the coarse adjustment to be used first and the one near the front being the fine adjustment. On the left-hand front corner is the double-throw transfer switch U; next to this is the low-scale plug K and to the right of this are the keys R_1, R_2 and R_0.

To explain the operation of this potentiometer, reference will be made to Fig. 16. The battery W sends a current, which is always adjusted so that it is exactly 0.02 ampere, through the circuit $WRKOADBW$. This current produces a drop of 0.1 volt in each of the 5-ohm coils between A and D. It also produces a drop of 0.1 volt in the slide wire $DM'B$, 10 turns of which have a resistance of exactly 5 ohms. It is seen that by adjusting the movable terminals M and M' the potential drop between them may be varied continuously from 0 to 1.6 volts. Consequently any electromotive force between 0 and 1.6 volts placed at the point marked E.M.F. may be balanced by adjusting the positions of M and M'.

It will now be explained how the potentiometer current can be adjusted so that it is exactly 0.02 ampere. If 0.02 of an ampere should flow through the 10 five-ohm coils included between F and A there would be a drop of 1 volt. Between A and the beginning of T there is a resistance of 0.85 ohm and the drop across this is 0.017 volt. The resistance of each coil in T is 0.005 ohm and the drop across each is 0.0001 volt. There are nineteen of these coils. Hence if the connection F is placed to include ten of the 5-ohm coils between it and A, the voltage drop between T and F may be varied in 0.0001-volt steps from 1.0170 to 1.0189 volts by changing the position of the arm on the rheostat T.

Let the standard cell be connected in the position shown and let the double-throw switch be put in the position marked STD. CELL. Suppose, for example, a certain standard cell has a voltage of 1.0180 volts. Set the rheostat T to include ten of its 0.005-ohm coils in the circuit between the points F and T. There will now be a resistance of $10\times0.005+0.85+10\times5=50.90$ ohms between T and F, and a current of 0.02 ampere in $OAFD$ will produce a voltage drop of 1.0180 volts between F and T. Under these conditions there will be no deflection of the galvanometer when the galvanometer key, shown at R_1, R_2, R_0, is depressed. The current may obviously be brought to exactly 0.02 ampere by adjusting the rheostat R until no deflection of the galvanometer occurs when its key is closed. The resistance between A and the beginning of T is not necessarily the same in all potentiometers. It can be changed to accommodate different types of standard cells.

A Weston standard cell is used. This is a particular form of galvanic cell carefully made according to definite specifications. The exact value of the electromotive force is given by the makers

with each cell. It is approximately 1.0180 volts but varies slightly for different cells, hence the necessity of the standard-cell rheostat T. The electromotive force is not affected by temperature.

To operate the potentiometer, connect the battery W (a storage cell will be used) and the Weston standard cell each to its proper pair of binding posts. *Be sure that the polarities are right.* Set the standard cell rheostat, T, at the voltage for which the particular cell to be used is certified. Connect the potential difference which is to be measured to the posts marked E.M.F. Be sure that the polarity is right. The potentiometer current must now be adjusted so that it is exactly 0.02 ampere. To do this throw the transfer switch, U, to the position marked STD. CELL, depress key R_1 and vary the rheostat R until the deflection is brought to zero. In case the deflection is always in one direction pull one or both of the plugs between the two rheostats. It should be possible to make the galvanometer deflection reverse by varying the coarse rheostat. When the deflection has been reduced to zero depress key R_2 which puts less resistance in the galvanometer circuit, making the instrument more sensitive, and again bring the deflection to zero. Now depress R_0, which cuts out all resistance, and use the fine part of R (the nearer handle) to obtain the final adjustment. When the balance is complete the potentiometer current is exactly 0.02 ampere and the drop across each of the 5-ohm coils is exactly 0.1 volt. As the resistance of each turn of the slide wire is 0.5 ohm the drop in each turn is now exactly 0.01 volt. After the potentiometer current has been adjusted throw the transfer switch U to the position marked e.m.f. This connects the source of potential difference to be measured in series with the galvanometer across the movable terminals M and M'. Now move M and M' to such positions that the galvanometer deflection is zero. When the final balancing is made the key R_0 should be used. The value of the unknown potential difference V_3 may now be read from the scales of the instrument. Read the slide wire M' just as you would read a micrometer. One turn of this slide wire corresponds to a potential difference of 0.01 volt. *As the potentiometer current due to W may not remain constant it must be checked frequently during the measurements.*

In case it is desired to measure a potential difference of less than 0.1 volt, the potentiometer current is balanced as before and then the plug K is shifted to the socket marked 0.1. This shunts nine-

tenths of the current through S (see Fig. 16) and makes the drop across all the resistance in $OAFMDB$ one-tenth of what it originally was, since the current in this part of the circuit is now one-tenth of its original value. To recheck for the proper value of the potentiometer current the plug must be replaced in socket 1.

In case it is desired to measure a potential difference of 1.6 volts or greater a volt box is used in connection with the potentiometer. One form of this device is shown diagrammatically in Fig. 18. In this particular volt box there are four resistance coils in series having values of 300 ohms, 2700 ohms, 27,000 ohms and 270,000 ohms. The potentiometer is always connected around the 300-ohm coil, the unknown potential difference is always connected around the 300-ohm coil plus one, two or three of the other resistances as the case may require. If it be connected to the extreme

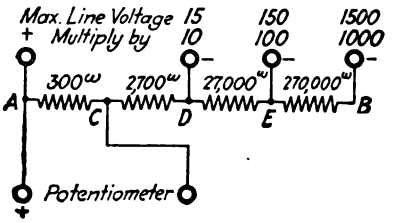


FIG. 18.

outside terminals the resistance is 300+2700+27,000+270,000 =300,000 ohms so that the drop between the potentiometer terminals, AC, is 0.001 of that between the main terminals, AB. With this connection a potential difference of 1600 volts, can be measured. If the line terminal is moved so that the resistance included is 30,000 ohms a potential difference of 160 volts can be measured, if the included resistance is 3000 ohms the limit is 16 volts. Note, however, that for voltages in excess of 1.6, the electromotive force can not be measured without drawing current from the source.

Procedure.—(A) Ammeter Calibration.

Make up an external circuit of a small storage battery, an ammeter, a standard resistance and a carbon-block rheostat for varying the current. The battery should be large enough to make the ammeter have a full-scale deflection when the rheostat is compressed and should be able to maintain the current constant.

Connect the potential terminals of the standard resistance to the electromotive force terminals, e.m.f., of the potentiometer. Compress the carbon-block rheostat until the ammeter shows a deflection of approximately one-tenth of full-scale reading, then balance the potentiometer. The drop across the standard resistance divided by the value of this resistance is the true current flowing. Vary the current by ten steps to cover the entire range of the ammeter being tested and measure the voltage drop across standard resistance for each step.

(B) **Voltmeter Calibration.**

Put a slide wire across direct-current mains of proper voltage and connect the voltmeter to be calibrated to one line and the slider. Connect the voltmeter to the proper terminals of the volt box and connect the 0-1.6-volt terminals of this box to the potentiometer. By means of the slide wire change the reading of the voltmeter in ten approximately equal steps from zero to full-scale reading, taking potentiometer readings at each point.

(C) **Wattmeter Calibration.**

First, by aid of a volt box calibrate a standard voltmeter at a point near line voltage. Have a slide wire rheostat in the voltmeter circuit so that the readings of the voltmeter may be kept at any desired value. Having calibrated the voltmeter, disconnect the volt box from the potentiometer and connect the potential coil of the wattmeter in parallel with the voltmeter through a reversing switch. Now treat the current coil of the wattmeter as if it were an ammeter. That is, make up an auxiliary circuit consisting of a battery, carbon rheostat, standard resistance and the current coil. Connect the potentiometer to measure the drop across the standard resistance. A reversing switch should be placed in series with the current coil of the wattmeter in order that the current in it may be reversed.

Now vary current in current coil of the wattmeter in about ten approximately equal steps from no-load to full-load current, measuring the drop across the standard resistance at each point. Keep the voltage on the wattmeter potential coil constant at the calibrated value. At each point take readings with current and potential coils of the wattmeter reversed, keeping the wattmeter reading *constant*. Use the mean of the reversed readings. All readings should be recorded. The true power at each step is equal to the true current times the true voltage.

Results Required for A, B or C.—

a. Date of calibration.

b. Serial number of instrument calibrated.

c. Diagram of actual connections.

d. Table of corrections.

e. Plot of corrections with corrections as ordinates and instrument readings as abscissæ. Be sure to give the algebraic sign of each correction. Use a broken line plot.

f. Explain how you could use a potentiometer to measure an *unknown resistance*, providing you had a standard resistance available.

[1] LAWS, "Electrical Measurements," p. 269.

[2] LAWS, "Electrical Measurements," p. 274.

LAWS, "Electrical Measurements," p. 273.

FARMER, "Electrical Measurements in Practice," p. 44.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. I, p. 75.

DAWES, "Electrical Engineering," vol. I, p. 153.

3

DIRECT-CURRENT WATTHOURMETER

In connection with the supply of electrical energy for lighting and power, it is necessary to have some form of integrating meter; that is, a meter which will give, not the rate at which energy is supplied to the circuit, but the total amount of energy supplied during a given time; in other words, a meter which will evaluate $\int_{t_1}^{t_2} vidt$, or for constant power give $VI(t_2-t_1)$; (t_2-t_1) being the time during which energy is supplied. In dealing with charges for electricity it is customary to express (t_2-t_1) in hours. The energy is then stated in watt-hours, or more frequently in kilowatt-hours, a kilowatt-hour being 1000 watt-hours.

A recording meter should possess the following characteristics: First.—It should maintain its accuracy under varying conditions of voltage and load. In general, the voltage on a system of electrical supply will remain nearly constant in the neighborhood of the station, expecially if the system be large; but at a distance, owing to insufficient copper in the conductors, the voltage variations may be considerable. The accuracy of the meter must not be affected by such variations. Accuracy at light loads is of great importance, for it is very seldom that the load in an installation is a maximum. Indeed, in the case of lighting, for a great part of the time a comparatively small portion of the lights are used. It is essential as a matter of business to have the energy correctly measured under light as well as heavy loads. Accuracy at full and intermediate loads is of course essential.

Second.—Permanency of calibration is a necessity. To attain this, the friction losses in the instrument must remain practically constant over long periods of time, and the magnets used in connection with the retarding disk must be permanent. This latter condition may be assured by the choice of a proper magnet steel,

correct design and artificial aging. The avoidable friction should be reduced as much as possible. To this end the moving parts should be light, with jewels and pivots which will remain in good order. The torque of the meter should be high, so that the unavoidable irregularities in friction may not cause inaccuracies, for in time both jewels and pivots become rough, especially if the meter be subject to vibrations and sudden jars. The changes of room temperature should not affect the calibration. Accuracy to within about 2 per cent. may be expected of instruments of this class if properly inspected and cared for.

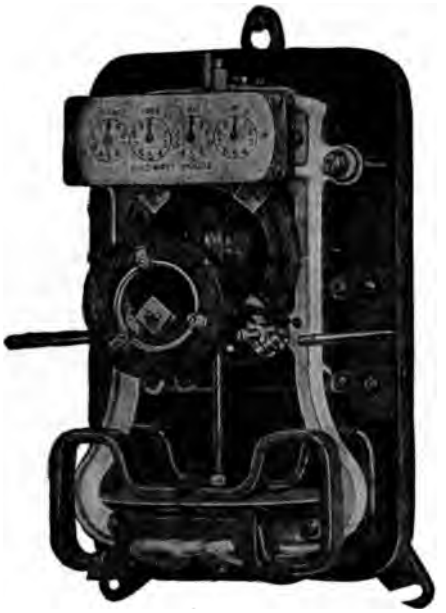


FIG. 19.

Third.—The energy losses in the meter must be small, for the instrument is in circuit continuously, even though the customer is using no current. Instruments of this class must be simple in design, so that the first cost and expense of maintenance will not be great. The meter should be protected by a case which is dust-, water- and insect-proof. The energy consumed should be registered on a series of direct-reading dials which are in full view of the customer, who is thus enabled to check the readings.

A typical meter with case removed is shown in Fig. 19.

The principle of the Thomson watthourmeter is that of a small motor, the torque of which is proportional to $I \times V$. This is resisted by the reaction of currents induced in a copper or aluminum disk attached to the shaft and moving between the poles of permanent magnets. The motor is without iron. The fields carry the line current. The armature, in series with a suitable resistance, is connected across the line. Reference to Fig. 20 will make the construction clear. The main current passes through the heavy coils F in series with the load. Situated between them is the drum armature A, which is wound on a light frame and is carried by an upright spindle. This is geared at the upper end to a very

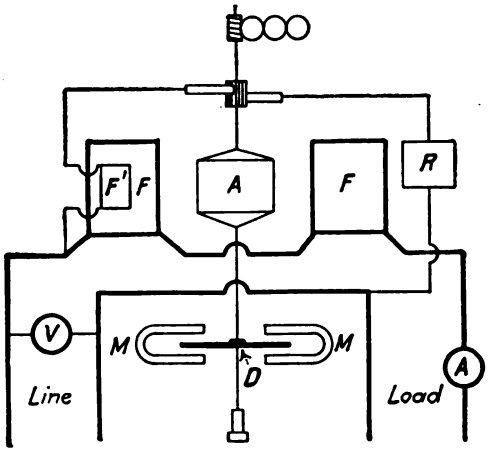


FIG. 20.

light train of wheels which move the pointers over the dials. Current is carried to the armature through silver-tipped brushes, which rest with very slight pressure on a silver commutator of small diameter. The brushes are adjusted before the instrument leaves the factory and should be very carefully treated. The commutator must be kept free from oil and dust of all kinds. The total resistance of the potential circuit is about 3000 ohms in a 110-volt instrument. The lower end of the shaft is provided with a removable pivot, resting in a sapphire jewel carried in a spring support in the end of a screw, which can be turned back so as to allow the disk D to rest upon the magnets M, where it can be wedged in position, thus relieving the pivot of all strain during transportation. The copper or aluminum disk D moves

between the poles of the permanent magnets M, whose distance from the axis of rotation may be altered, thus changing the retarding force.

In order to compensate the effects of mechanical friction, a field coil of fine wire is connected in series with the armature thus giving a small permanent driving torque, so that the meter is just on the point of starting when at no load. The effect of this coil at the higher loads is insignificant. The potential circuit is connected on the supply side of the main coils.

To show that the number of revolutions during a given time is proportional to the energy we may proceed as follows: Let I_L be the load current; V_t the voltage of the mains; ω, the angular velocity of the armature; G, a constant depending on the field coils; G', a constant depending on the compensating coils; A, a constant depending on the armature; R, the resistance of the potential circuit; h, a constant depending on the strength of the field of the magnets; r, a constant depending on the resistance of the retarding disk; X, the pivot friction.

Since torque $= k\phi I_a$ where ϕ is field flux which is proportional to line current I_L (except for the flux due to the light-load coil, F', which flux is proportional to I_a) and I_a is the armature current which is equal to $\frac{V_t}{R}$, the driving torque is

$$I_L G \frac{V_t}{R} A + \left(\frac{V_t}{R}\right)^2 AG'.$$

The retarding torque is

$$\frac{h^2\omega}{r} + X.$$

For steady motion

$$I_L G \frac{V_t}{R} A + \left(\frac{V_t}{R}\right)^2 AG' = \frac{h^2\omega}{r} + X.$$

If compensation for the friction is exact, that is, if $\left(\frac{V_t}{R}\right)^2 AG' = X$,

$$I_L V_t = \frac{h^2 R}{GAr}\omega,$$

and the velocity of rotation is seen to be proportional to the rate of expenditure of energy. $I_L V_t(t_2 - t_1) = \frac{K\omega}{2\pi}(t_2 - t_1) = K \times$ total number of revolutions.

Therefore, for meters as actually constructed,

$$\text{Watts} \times \text{hours} = K \times \text{number of turns.}$$

When the meter is calibrated it is usual to observe the time necessary for a given number of turns. Suppose that N turns are made in t seconds, then

$$K \times N = \text{watts} \times \frac{t}{3600},$$

where K is the number of watt hours per revolution and is the constant of the meter (usually found marked on the retarding disk) and 3600 the number of seconds in an hour. That is, the watt hours (energy) are equal to the product of the meter constant and the revolutions of the rotating element. The rotating element is so geared to the clock work that the hands on the dial register the kilowatt hours *if the adjustment of the moving element has been correctly made.* If the energy is supplied at a constant rate,

$$\text{Power} = P = \frac{KN3600}{t}.$$

As the armature circuit carries current and is in part made of copper, its resistance will rise when the meter is first connected in circuit. Consequently tests should not be made until the permanent state of temperature has been attained. This may require about twenty minutes.

It is evident that the temperature coefficients of R and of the retarding disk should be nearly the same in order to reduce the temperature coefficient of the meter to a minimum.

Procedure.—To check the meter, apply a load by means of a lamp bank and measure the power supplied to the lamp bank by means of a calibrated ammeter and voltmeter, connected as shown in Fig. 20. The ammeter should be protected by means of a short-circuit block.

The disk should rotate from left to right when viewed from the front. Make several determinations of the time required for the disk to make a definite number of revolutions, using a stop watch to measure the time. Record the average current and voltage of the load during each determination. The duration of a run should be approximately one minute. The average watts, according to the watthourmeter, may be found from the above equation. The

true average watts are calculated from the average of the voltmeter and the ammeter readings. The ammeter and voltmeter should be read at definite intervals during each run by one of the observers. The other observer should take the time required for a counted number of the revolutions of the disk with a stop watch.

The meter should first be checked, *as found*, at from 5 per cent. to 10 per cent. rated full load, and at rated full load, before adjustments are made. The meter should then be adjusted to within 1 per cent. First make runs at rated full load, bringing the meter to within 1 per cent. of the correct value by moving the magnets. When this adjustment is properly made the load should be dropped to from 5 per cent. to 10 per cent. of its full-load value, and the adjustment made by moving the starting coil (F') which compensates for friction. The load should then be increased to the rated full-load value and the meter checked in order to be certain that the light-load coil has not affected the accuracy of the meter at full load.

When these adjustments have been correctly made check the meter to full load in steps of about 20 per cent. of the rated full load, without disturbing the adjustments already made.

$$\text{Per cent. of accuracy} = \frac{\text{Registered watts}}{\text{True watts}} = \frac{P}{VI} \times 100.$$

This percentage will be greater than 100 per cent. if the meter overregisters.

$$P = \text{watts from formula} = \frac{KN3600}{t},$$

and

V = line voltage,

I = line current.

Results Required.—

a. A plot of "per cent. of accuracy" against percentage of rated full-load current. Draw broken line plot.

b. Diagrams of actual connections of the meters.

c. An explanation of the principle of the meter.

d. What is the effect of change of room temperature on the action?

e. Explain in detail the light load adjustment.

f. Explain why moving the magnets changes the meter speed.

g. If a meter is calibrated with the ammeter and voltmeter connected as shown in Fig. 20, who pays for the energy expended in the current coils when the meter is actually used?

h. Who pays for the loss in the potential circuit.

i. Why should the ammeter be connected on the load side of the meter?

j. Why is this arrangement just?

k. Plot " per cent. of accuracy " against " per cent. rated voltage " for one-tenth rated current and voltage varring from 30 per cent. below to 30 per cent. above rated value. Repeat for full-load current.

l. What effect does over voltage have on the percentage accuracy?

m. Would you expect the meter to speed up or slow down with age? Give reasons.

n. In what way do stray fields affect the accuracy of the meter?

o. How does the construction of a three-wire instrument differ from the two-wire?

LAWS, "Electrical Measurements," p. 457.

"Electrical Meterman's Handbook," chap. VII.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. I, p. 99.

DAWES, "Electrical Engineering," vol. I, p. 162.

4

CONDUCTIVITY

The Wheatstone bridge is adapted to the measurement of resistances which are large compared to any of the contact resistances in the bridge network. If the contact resistances at the terminals of the element being measured become appreciable when compared to the resistance of the element itself an error is obviously introduced and it is one which cannot be readily eliminated on account of the variable nature of contact resistances. Also, where measurements are made to determine the conductivity of a certain material it is necessary that the stream lines of current be parallel throughout the length of the specimen, otherwise the voltage gradient will not be the same at all points and the true conductivity cannot be determined. The Wheatstone bridge is not adapted to this kind of a measurement, for it is impossible to keep the current properly distributed at the terminals and eliminate the effect of contact resistances.

Suppose the conductivity of a certain uniform copper rod is desired. If a fairly large, known current is passed through the rod and a high resistance voltmeter is connected between points on the rod which are a known distance apart the conductivity can theoretically be determined, because the effect of the high-resistance voltmeter would not alter the current flow appreciably and knowing the voltage drop across a known length and the current flowing, the resistance per centimeter cube would be

$$\rho = \frac{V}{I} \cdot \frac{A}{l} \text{ ohms per } cm^3,$$

where A is the cross sectional area of the rod in square centimeters and l the length in centimeters across which the voltage was measured. The conductivity would be

$$\gamma = \frac{I}{V} \cdot \frac{l}{A} \text{mhos per } cm^3.$$

The disadvantages of this method are that the current and voltage must be measured simultaneously, and that the measurements cannot be obtained to the usual precision required.

It is possible, however, to replace this volt-ammeter arrangement by the bridge net-work shown in Fig. 21, which is an adaptation of the Wheatstone bridge.

The bar ab is a standard resistance and the resistance R between the contact points a and b is therefore known. The bar $a'c$ is the unknown of which the conductivity is to be determined. R_M and R_N are the arms of an ordinary bridge box and G the galvanometer. R_C is the resistance between a and a' and is made up of contact and lead resistances.

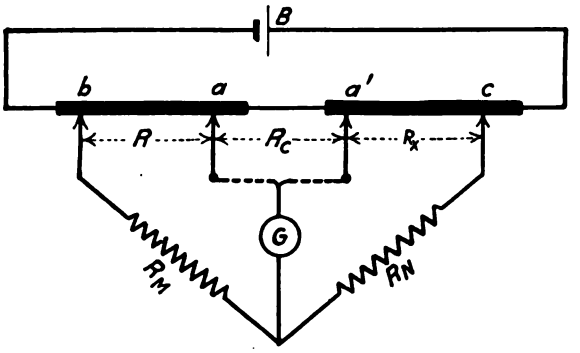


FIG. 21.

If the galvanometer is connected to a and the resistances R_M and R_N varied until the deflection is zero

$$\frac{R}{R_C+R_X}=\frac{R_M}{R_N}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If the galvanometer terminal is shifted to a' and the bridge balanced

$$\frac{R+R_C}{R_X}=\frac{R_M'}{R_N'}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Eliminate R_X from equations (1) and (2) as follows:

From (1)

$$R_X=\frac{RR_N}{R_M}-R_C,$$

and from (2)

$$R_C = \frac{R_X R_M'}{R_N'} - R,$$

$$R_X = R\frac{R_N}{R_M} - \frac{R_X R_M'}{R_N'} + R,$$

$$R_X\left(1+\frac{R_M'}{R_N'}\right) = R\left(\frac{R_N}{R_M}+1\right),$$

$$R_X = R\frac{(R_M+R_N)}{(R_M'+R_N')}\cdot\frac{R_N'}{R_M}.$$

This determination of R_X is independent of R_C provided R_C remains constant. It should remain constant because it is not touched while the measurements are being made. The contacts a' and c are point contacts which are a known distance apart. The resistance R_M and R_N are very large compared to R and R_X, consequently the current taken by the bridge arms does not alter the distribution of current in the specimen.

The accuracy of the bridge setting increases with the current but care must be taken that the specimen does not become too hot for high temperature means non-uniformity in temperature distribution and consequently non-uniform conductivity.

To obtain reliable results the specimen must be placed in an oil bath and the oil kept well circulated in order to insure uniform temperature.

This method may be used to determine the temperature coefficient by simply measuring the resistivity at two known temperatures.

Procedure.—In arranging the circuit for the test be sure that all joints in the R_C portion of the circuit are tight so that there can be no variation in the resistance R_C. Make the potential contacts a' and c firm but do not apply sufficient pressure to disfigure the specimen or dull the point contacts. Connect short wires from a and a' to dummy binding posts so that the galvanometer lead may be attached to these posts and thus make it unnecessary to disturb a and a' during the test. Use short leads to connect R_M and R_N to b and c respectively and make good contacts because these lead and contact resistances are part of R_M and R_N. Use large enough values of R_M and R_N to make these lead and contact resistances negligible compared to R_M and R_N.

Have the oil bath circulating freely and take temperature of oil periodically during the test.

Make check measurements with battery reversed and take the average for the result in order to eliminate thermoelectric effects.

Make several measurements of the specimen dimensions and average for final result.

Results Required.—

(*a*) Explain the operation and theory of the test.

(*b*) Compute for each specimen the following values at the bath temperature:

1. Resistance per linear centimeter.
2. Resistivity in microhms per centimeter cube.
3. Resistivity in ohms per meter-gram.
4. Resistivity in ohms per mil-foot.
5. Per cent. conductivity.

(*c*) Per cent. conductivity at 20° C.

(*d*) Circular mileage of specimen.

(*e*) Temperature coefficient of resistance at 20° C.

(*f*) If measurements are made at two different temperatures for the determination of temperature coefficient should the linear measurements be obtained for each temperature or should they be made at only one temperature and those at the other temperature be computed by means of the temperature coefficient of expansion? Give reasons.

(*g*) Probable sources of error.

LAWS, "Electrical Measurements," p. 190.
FARMER, "Electrical Measurements in Practice," p. 133.

CABLE TEST

In cables used for light and power or for communications circuits, continuous operation is necessary. In case of short circuits, grounds or open circuits, it is necessary to be able to locate the fault quickly and accurately in order that the trouble may be repaired without delay. There are many methods of locating shorts and crosses depending on what auxiliary circuits are avail-

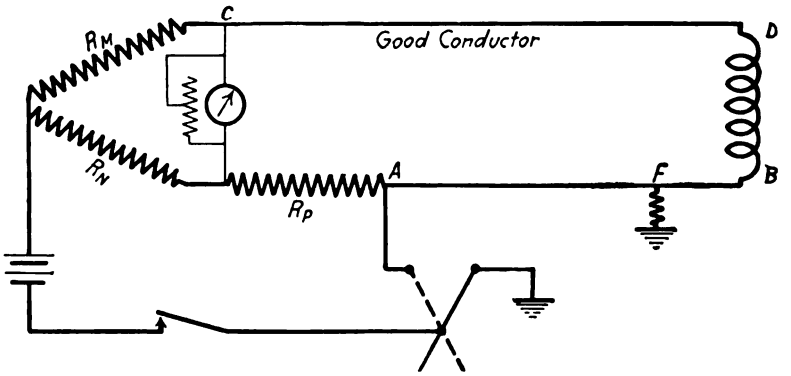


FIG. 22.

able. The reader will find a most complete discussion in Laws' "Electrical Measurements," Chapter XV.

One commonly used method for locating a ground or cross is the Varley loop test. This method requires that one good conductor shall parallel the faulty one.

The two lines are connected at the far end by a wire of approximately negligible resistance. See Fig. 22.

Let the resistance from A to F be R_X and the resistance from F through B to D and C be R_Y. With the switch S in the position shown solid, we have for zero galvanometer deflection

$$\frac{R_X+R_{P_1}}{R_Y}=\frac{R_{N_1}}{R_{M_1}}. \quad \ldots\ldots\ldots \quad (1)$$

Now with the switch in the position shown dotted we have for balance,

$$\frac{R_X+R_Y}{R_{P_2}}=\frac{R_{M_2}}{R_{N_2}}, \quad \ldots\ldots\ldots \quad (2)$$

which gives us two equations and two unknowns, so we may solve for R_X and R_Y. Knowing R_λ and the resistance per unit length from the size of wire and assuming an approximate temperature, the distance to the fault may be calculated.

A short between two conductors in paired cable is located similarly. In this case the battery is connected to one of the shorted conductors instead of to ground. The other faulty conductor is connected to R_P as before.

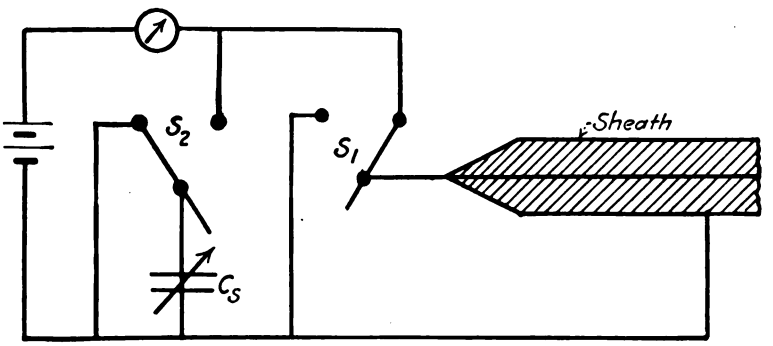


FIG. 23.

In the case of an open circuit or total disconnection, the distance to the break may be determined by measuring the capacitance of the line when open. If the capacitance of the line before the breakdown is known (as it would ordinarily be from office records) the distance to the fault may be calculated knowing that the capacitance is a direct function of the length. If the total capacitance is not known, the capacitance measured from both ends will give the total. See Fig. 23.

The capacitance is measured by charging the cable through a ballistic galvanometer, whose deflection is proportional to the quantity of electricity and consequently proportional to the capacitance of the cable. This is done by throwing S_1 to the right and recording the deflection of G. If now the cable is discharged by throwing S_1 to the left and S_2 is thrown to the right and the deflection due to the charging of C_S from the same battery assumed to be of con-

stant voltage, is noted, the capacitance of the cable may be calculated.

$$\frac{C_S}{C_X}=\frac{D_S}{D_X},$$

where C_X is the capacitance of the cable to the break, D_S is the deflection due to the charging of C_S and D_X is the deflection due to the charging of C_X. C_S may be variable, but if it is not the deflections of the galvanometer may be kept on scale by means of an Ayrton shunt such as was used in the Wheatstone bridge experiment. In the testing of telephone cables C_S may be a good pair free at the far end and C_X the pair of which one lead is broken.

Procedure.—Assuming a real or artificial cable available which can be grounded at some point, and that we also have a spare good cable for the return path, measure the resistance to the ground, using the Varley loop test.

Now free the faulty cable from ground, but leave it continuous and measure the capacitance. Now open the cable at any convenient point and measure the capacitance to the break.

Results Required.—

a. Calculate the resistance to the ground. Knowing the size of wire, calculate the distance to the ground.

b. Distance to break.

c. If ground and break are taken at the same point compare distances obtained by means of the two methods.

DAWES, "Electrical Engineering," vol. I, p. 148.

6

INDUCTANCE AND CAPACITANCE MEASUREMENT BY BRIDGE METHOD

There are a number of special bridges used for the measurement of inductance and capacitance, but of these the Wheatstone type is the most common and will be described here. Referring to Fig. 24, it will be noted that the set-up is the same as that of Fig. 13, except that the arms Z_X and Z_P contain inductance and

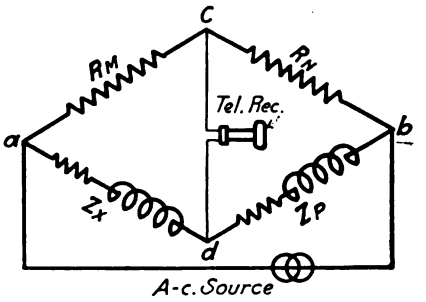


FIG. 24.

the source is alternating current instead of direct. The galvanometer must be of the vibrating or dynamometer type in order to be responsive to alternating currents. If a frequency of from 200 to 1500 cycles is employed a telephone receiver may be used for a detector.

Let R_X and L_X be the resistance and inductance of the unknown branch and R_P and L_P the resistance and inductance of the known branch Z_P. Then in order for the galvanometer to be zero,

$$I_{ad} = I_{db} \quad \text{and} \quad I_{ac} = I_{cb}, \quad . \quad . \quad . \quad . \quad . \quad (1)$$

also

$$V_{ac} = V_{ad} \quad \text{and} \quad V_{cb} = V_{db}. \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The above relations must not only be true numerically but vectorially as well.

From (2) it follows that

$$I_{ac}R_M = I_{ad}(R_X + j2\pi fL_X),$$

and

$$I_{cb}R_N = I_{db}(R_P + j2\pi fL_P).$$

$$\frac{R_M}{R_N} = \frac{R_X + j2\pi fL_X}{R_P + j2\pi fL_P},$$

then

$$R_X + j2\pi fL_X = \frac{R_M}{R_N}(R_P + j2\pi fL_P),$$

and since the reals and imaginaries must each satisfy the equality

$$R_X = \frac{R_M}{R_N}R_P \quad \text{and} \quad L_X = \frac{R_M}{R_N}L_P.$$

If capacitance were being determined, the arm Z_P would have to contain capacitance instead of inductance, and

$$R_X - \frac{j}{2\pi fC_X} = \frac{R_M}{R_N}\left(R_P - \frac{j}{2\pi fC_P}\right),$$

from which

$$R_X = \frac{R_M}{R_N}R_P \quad \text{and} \quad C_X = \frac{R_N}{R_M}C_P.$$

From the above equations it is seen that the bridge must be in balance for the resistances in the various arms as well as for the inductance or capacitance.

Procedure.—Make connections as shown in Fig. 24. To balance bridge, first adjust the inductance (L_P) or capacity (C_P) until the galvanometer deflection is a minimum, then vary R_P until the deflection is again a minimum, then readjust L_P or C_P, and continue in this way until the best possible balance is obtained.

Results Required.—

a. Inductance and resistance of any coil *Q*.
b. Inductance and resistance of any coil *R*.
c. Inductance and resistance of coils *Q* and *R* in series.
d. Inductance and resistance of coils *Q* and *R* in parallel.
e. Repeat *a*, *b*, *c* and *d* for any condensers *J* and *K*.
f. Determine the mutual inductance of two coils when parallel.

LAWS, "Electrical Measurements," p. 381.

7

INDUCTION WATTHOURMETER

The induction watthourmeter, as its name implies, makes use of the same principles for its operation as does the induction motor. The rotating element, which usually consists of a flat aluminum disk, is not connected electrically in any way to the circuit in which the meter is installed. The disk is subjected to the action of two alternating fluxes, one being set up by the current in the potential

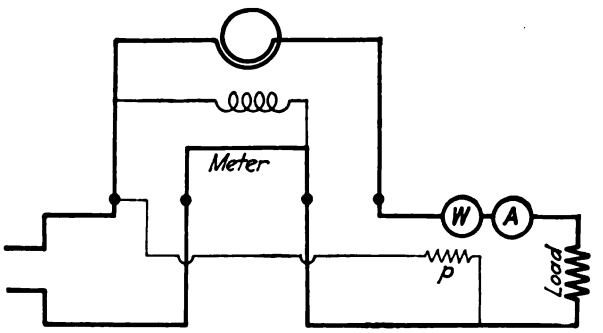


FIG. 25.

circuit, and the other by that in the series or current circuit. Each of these fluxes being alternating induce currents in the conducting disk. The current in the disk due to the potential circuit flux reacts with the current circuit flux and produces a driving torque, and the current in the disk due to the current circuit flux reacts with the potential circuit flux and produces a driving torque. The arrangement of the electric circuits of the meter will be made clear by referring to Fig. 25.

Due to the high inductance of the potential circuit winding the potential-circuit current lags the voltage by nearly 90°, consequently, if the power factor of the load is unity the potential and current-circuit fluxes will be almost in quadrature. An exact

quadrature relation is obtained for the fluxes cutting the disk by means of the lag coil. It is essential that these fluxes be in time quadrature at unity power factor, otherwise the registration for a load current which lags the voltage by the angle θ would not be equal to that obtained when the same current leads the voltage by the same angle. In other words the meter would not be accurate at all power factors.

If the fluxes are in time quadrature at unity power factor, the driving torque at any power factor is proportional to the product of the two fluxes and the sine of the angle $(90° - \theta)$ between them.

$$T = K\phi_p\phi_I \sin (90° - \theta), \quad P = VI \cos \theta.$$

In order to maintain this relation for all conditions of load, the reluctances of the magnetic circuits and the resistance and inductance of the electric circuits must be constant. This condition is closely approached by having numerous air-gaps in the magnetic circuit and by working the iron at low saturation.

At light load the frictional torque is comparable with the driving torque. In order, therefore, to obtain correct registration, a driving torque which is approximately equal and opposite to the frictional torque must be introduced. The result is accomplished by inserting a short-circuited loop of low resistance (usually called a stamping) in the air-gap. By shifting this loop from the symmetrical position the flux distribution is altered and the phase shifted thus producing a driving torque.

This light load adjustment is solely for the purpose of compensating for the frictional torque and has a negligible effect when the meter is loaded. Care must be taken not to over-compensate for the frictional torque because a jarring of the meter is then apt to cause creeping even though there is no load on it.

The full-load adjustment is the same as in any watthourmeter and consists simply of shifting the breaking magnets until proper registration is obtained.

Procedure.—With a load of approximately 15 per cent. adjust the light load lever until the registration is correct to within $\frac{1}{2}$ per cent. Now with full-load adjust the breaking magnets until the registration is correct to within $\frac{1}{2}$ per cent. Make the following runs taking readings in steps which are 20 per cent. of full-load value:

1. Calibration at 100 per cent. power factor.

2. Calibration at 50 per cent. power factor (lagging current).
3. Calibration at 50 per cent. power factor (leading current).
4. Repeat runs 2 and 3 but with the compensation circuit open.

Results Required.—

a. Plot of ratio of registered power to true power, against true power (broken line pot) for each run.

b. Calibration at 50 per cent. load current, unity power factor, for a voltage range of 30 per cent. below to 30 per cent. above rated voltage.

c. Discuss fully the effect of temperature variation on the accuracy of the meter.

LAWS, "Electrical Measurements," p. 473.
KARAPETOFF, "Experimental Electrical Engineering," 2nd. Ed., vol I, p. 107.
DAWES, "Electrical Engineering," vol. II, p. 63.

8

INSTRUMENT TRANSFORMERS

In direct-current work, when it becomes necessary to measure large currents, ammeters with external shunts are employed. In alternating-current measurements this cannot be done, for both the ammeter and its shunt possess reactance as well as resistance so that the current will not divide according to the simple " law of shunts " which is true only for direct currents.

When large alternating currents are to be measured ammeters operated through current transformers are employed. The primary winding of a current transformer has comparatively few turns, it is inserted in the line and consequently carries the entire line current. The secondary winding usually has a larger number of turns and is connected directly to the ammeter. The result is that a large line current will set up a small current through the ammeter. The ratio of the primary to the secondary current, commonly called the ratio of the transformer, is *approximately* equal to the ratio of the numbers of the secondary and primary turns.

The advantages obtained by the use of current transformers are the complete insulation of the ammeter from the line, which may be at a high voltage, and the ability to use low-range ammeters for the measurement of large currents.

It is customary to employ only 5-ampere ammeters on switchboards irrespective of the magnitude of the current to be measured and to so graduate their scales that the line current can be read off directly. This can be done because current transformers having 5-ampere secondaries are made in a great variety of ratios.

The use of current transformers reduces the cost of switchboard installation, for only one size of ammeter has to be provided irrespective of the magnitude of the current to be measured and the installation of heavy buses to and from the measuring instruments

is avoided. It also avoids the necessity of having any high-voltage current leads on the switchboard.

The secondary circuit of a current transformer should never be opened while the transformer is operating, for this would remove the demagnetizing effect due to the secondary current and allow the flux to rise to a high value causing a large hysteresis loss and consequent damage from overheating. A high voltage would be induced in the secondary, which would be a source of danger and might puncture the secondary insulation. Also the ratio of the transformer might be altered, for if the core happened to be left in a highly magnetized condition the transformer would thereafter operate with an abnormal iron loss and magnetizing current.

In direct-current work high voltages are measured by using a voltmeter in series with a multiplier, the same arrangement is frequently employed in alternating-current measurements, up to about 3000 volts. At high voltages the power lost in the voltmeter and the multiplier becomes large. In many measurements this necessitates troublesome corrections. Of greater importance, however, is the disadvantage that high voltage leads, which are a source of danger, must be brought to the switchboard.

To avoid these difficulties potential transformers are used. They are similar to ordinary constant-potential transformers only more carefully constructed. The primary is wound to operate across the line and the ratio is such that the secondary which is connected to a voltmeter or to the potential coil of a wattmeter will deliver 110 volts for rated primary voltage. They are made in a number of ratios to accommodate the standard primary voltages. This means that all switchboard instruments can have 150-volt potential coils and that 110 volts is the maximum voltage at the switchboard. That reduces the danger of shocks to a minimum and enables the operator to act with confidence, especially in emergencies.

When measuring power in an alternating-current circuit a current transformer and a potential transformer are usually employed. The former lowers the current to be carried by the instruments, while the latter decreases the voltage impressed upon them.

Let a_I = the ratio of transformation of the current transformer;

I_P = line current;

I_S = secondary current;

a_V = the ratio of transformation of the potential transformer;
V_P = line voltage;
V_S = reading of secondary voltmeter;
P_P = line power;
P_S = reading of secondary wattmeter;
k = constant of wattmeter.

Then,

$I_P = a_I I_S$, $V_P = a_V V_S$, and $P_P = a_I a_V k P_S$.

The terminal of the potential transformer going to the zero post of the wattmeter should be grounded as well as one terminal of the secondary of the current transformer. In case the wattmeter reads backwards reverse the current coil.

Procedure.—Power is to be supplied to a load from a 230-volt line. The power, the current and the voltage taken by the load are to be measured by instruments inserted directly in the line and also by instruments operated through instrument transformers as shown in Fig. 26.

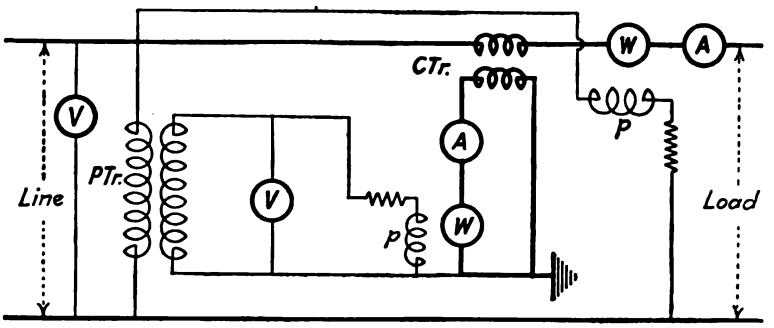


FIG. 26.

Use transformers of such ratios that you can employ instruments with 5-ampere current coils and 150-volt potential coils.

With a non-inductive load vary the current from one-fifth full load to full load by steps. Repeat the above measurements using an inductive load of 40 per cent. power factor. This may be obtained by connecting a reactance in parallel with the resistance.

The calibration corrections for the meters and the true ratios of transformation of the current and potential transformers should be given. Note the corrections and ratios of transformation for the readings taken, before leaving the laboratory.

Results Required.—

a. For both runs, curves of power taken by load obtained from secondary wattmeter, using instrument transformer ratios, against power taken by load obtained from primary meters. Make corrections for any power taken by the instruments. Compare these two sets of curves, and explain any discrepancies.

b. Why is it necessary to ground the secondaries when measurements are made on high-voltage circuits?

c. What are the losses in the instrument transformers?

d. Explain the instrument corrections in detail, telling why and how they are made.

e. Plot of current transformer ratio against secondary current, as determined from readings of primary and secondary meters.

f. Ratio of potential transformer at line voltage as determined from data taken.

LAWS, "Electrical Measurements," chap. XII.
DAWES "Electrical Engineering," vol. II, p. 220.

9

RESISTANCE MEASUREMENTS OF ARMATURE AND FIELD

The resistance of a dynamo armature is of a comparatively low value and varies with the capacity of the machine. Machines of 1-kw., 115-volt rating may have a resistance of approximately an ohm while the armature resistance of a 25-kw. machine may be about two or three hundredths of an ohm. The resistance of armatures of large machines will be still smaller, decreasing with an increase in size.

The value of field resistance varies with the capacity of the machine in this same way, from 250 ohms for the 1-kw. 115-volt machine down to 20 ohms for the 25-kw. machine.

The resistances of the windings of a machine are also functions of the voltage and speed for which the machine is built, and moreover, they depend to a large extent upon the type of the design adopted. Machines of different designs but of the same kilowatt, speed and voltage ratings may have quite different resistances. Machines of the same type and equal kilowatt and speed ratings will have resistances which are substantially proportional to the squares of their voltage ratings. Machines of the same general type and equal voltage ratings but of different kilowatt ratings will have resistances which, in a general way, are inversely proportional to their kilowatt ratings provided these ratings do not differ too greatly. The resistances will be found to decrease more rapidly than this last rule would indicate, due to the higher efficiencies and smaller losses of the larger machines.

Procedure. Resistance of the Armature Circuit Including the Brush Resistance.—Connect the armature of the machine to be tested to the mains in series with a rheostat and ammeter of proper size as shown in Fig. 27. Attach a voltmeter to the armature terminals outside of the brushes. Vary the current by means of the rheostat and read the voltmeter for values of current from

0.25 rated current to 1.25 rated current recording readings for five or six steps.

Due to the low resistance of armatures and series fields of motors and generators it is always necessary to place an auxiliary resistance

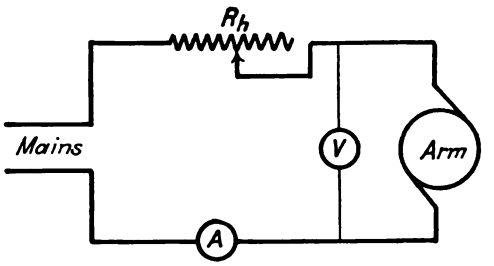


FIG. 27.

in series with them to limit the current when measuring the resistance by the drop-in-potential method. Such a resistance is not necessary in the measurement of the shunt field resistance providing the line voltage does not exceed the rated voltage of the machine under consideration.

Resistance of the Armature Circuit Alone, not Including Brush Resistance.—Repeat the above procedure with the voltmeter connected to the commutator segments which lie directly beneath the centers of the brushes.

Brush and Brush-contact Resistance.—Again repeat with one terminal of the voltmeter connected to one of the brush holders and the other one to the commutator segment which is directly beneath the brush. Then repeat with one terminal of the voltmeter on the commutator and the other on the brush directly above.

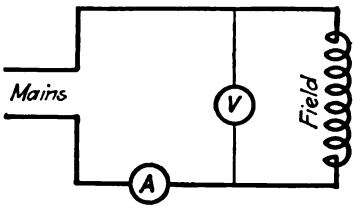


FIG. 28.

Field Resistance.—Connect the shunt field to mains of rated voltage as shown in Fig. 28. Measure terminal voltage and field current. Be sure to disconnect the voltmeter before opening main switch in order to protect the voltmeter from field discharge.

Results Required.—

a. Plot resistance of armature circuit versus armature current.

b. Plot resistance of armature winding versus armature current.

c. Plot brush and brush contact resistance versus current density in the brushes in amperes per square inch.

d. Plot brush and brush contact voltage drop versus current density in amperes per square inch.

e. Resistance of field circuit.

f. Give a complete explanation of the results obtained.

g. Select several machines of different sizes, but the same voltage rating and determine how R_a and R_f vary with size.

h. Select two or more machines of the same size, but different voltage ratings, and determine how R_a and R_f vary with voltage rating.

i. Calculate the current density in the brushes when the machine delivers rated current. Compare this with the handbook values for the type of brushes used.

See Experiment 12.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. I, p. 2.

10

DIRECT-CURRENT GENERATOR CONNECTIONS

One of the most simple forms of direct-current generator is the gramme ring machine. This type is not used because it requires too much copper and has many other disadvantages. The drum type is universally used. The armature coils are form wound and embedded in the armature slots. The armature coils may be connected in various ways. The two types of winding in common use are the simplex lap or parallel and simplex wave or series.

The shunt field of a direct-current generator may be either separately or self-excited. When the field is separately excited, the generator will develop voltage for either polarity of field and either direction of rotation. When the field is self-excited the generator may not develop rated voltage for the following reasons:

1. Residual magnetism is absent.
2. Field resistance is too high or field circuit open.
3. Machine is running below its rated speed.
4. Improper connection of the field for the direction of rotation.
5. Brushes are improperly placed.

When the generator is being driven in a certain direction the connection of the field is fixed. The field must be connected to the armature in such a way as to make the flux due to the field current have the same direction as the residual flux. The generator will not deliver voltage if the field connection is reversed unless the direction of rotation is also reversed. Reversal of the direction of rotation will necessitate a reversal of the field in order to make the machine build up to voltage.

A reversal of residual magnetism will result in a reversal of the generator polarity.

Procedure.—Connect the shunt field of the generator to be tested to the laboratory mains through a field rheostat of the proper resistance and current-carrying capacity. Record the voltage

across the armature when the generator is driven at rated speed and also when driven at approximately half speed. In both cases adjust the field for maximum flux and set the brushes for maximum voltage. Reverse the field connections and repeat, being careful to record the polarity in each case.

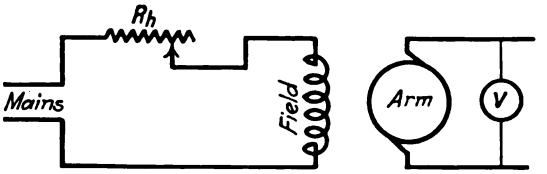


FIG. 29.—Separately excited.

Disconnect the field from the mains and note the direction of the voltage produced by the residual flux.

Connect the field to the armature and cut out the field resistance. Record the polarity of the armature and its voltage. Make field resistance a maximum and note polarity and voltage.

Reverse the field and repeat.

Reverse the direction of rotation and repeat the last two runs.

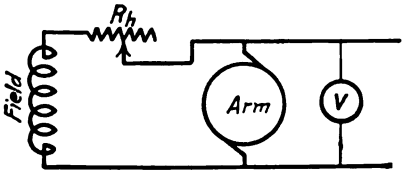


FIG. 30.—Self-excited.

Results Required.—

a. A table of all results and an explanation of them.

b. Why is not the voltage directly proportional to speed in a self-excited shunt generator with constant field resistance?

c. Explain fully why in two cases above decreasing field resistance decreases voltage also.

d. Take a magnetization curve at one or more speeds for both increasing and decreasing flux and explain.

e. What portion of the magnetomotive force is required for the air gap?

f. For a constant excitation, how does the e.m.f. vary with the position of the brushes? Plot a curve of voltage versus brush position expressed in electrical degrees.

g. What is the field copper loss at no load and rated voltage?

h. What is the critical field resistance for rated speed?

i. What is the critical speed for the field resistance which gives rated voltage at rated speed?

j. Examine the brushes and note whether copper, hard carbon or soft carbon is used.

k. Calculate the current density in the brushes at full load.

l. Calculate the average volts per commutator segment.

DAWES, "Electrical Engineering," vol. I, chaps. X and XI.

LANGSDORF, "Principles of Direct-Current Machines, 2nd Ed., chaps. III and VI.

HUDSON, "Engineering Electricity," chap. IV.

11

POTENTIAL ABOUT THE COMMUTATOR

A study of the potential induced in the armature coils of a motor or generator when in different parts of the field is important. From such a study the amount of field distortion due to the load and its effect on the operation of a machine may be determined. The commutation of a machine and the tendency of a machine to flash over under load may also be predicted.

There are several methods by which the variation of the potential about the commutator of a generator or motor may be deter-

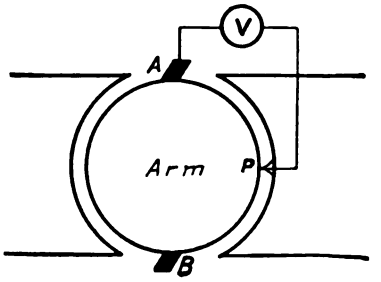


FIG. 31.

mined. The one which will be used in this experiment employs a single pilot brush. Starting from either the positive or the negative brush on a motor or generator, this method adds the potentials produced in the armature coils which lie between one brush and any given point in the field.

The fields of the generator to be tested should preferably be disconnected from the armature and separately excited, i.e., excited from some external source. The armature should be driven at a constant speed.

One terminal of a voltmeter is attached to the brush, A, of the generator, the other terminal is attached to a small movable pilot

brush, P, which can be moved about the commutator. If the pilot brush is placed at A, the two brushes will be at the same potential and the difference of potential between them will be zero. If the pilot brush is moved to B, the potential difference between it and A will be a maximum and equal to the potential of the generator. If now, P, starting at A, is slowly moved about the commutator, the reading of the voltmeter will gradually increase and will become a maximum when P reaches B. It will then decrease and finally become zero again when P gets back to A.

The result may be plotted as in Fig. 32, in which electrical degrees are abscissæ and volts are ordinates.

The slopes of the different parts of this last curve show the relative activity of the armature coils when in different positions

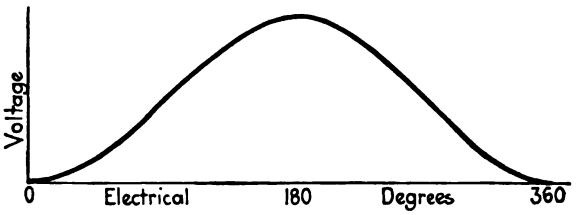


FIG. 32.

with respect to the field. The voltage induced in a coil when no distortion is present is a minimum, or zero, when the plane of the coil is at right angles to the field axis, the coil sides being at 0° and 180° with reference to the interpolar axis; and should be a maximum when the plane of the coil is parallel to the field axis, the coil sides in this case being at 90° and 270°. This is shown in Fig. 32 by the flatness of the 0° and 180° points and the steepness of the 90° and 270° points. Curves of this sort serve to show the best position for the brushes as well as the distribution of the flux in the air-gap.

The slope, at any given point, of the curve shown in Fig. 32 is proportional to the flux density in the air-gap at that point. This slope may be found from a line drawn tangent to the curve at the given point. The tangent of the angle this line makes with the axis of abscissæ is proportional to the flux density. This method of finding flux densities is unsatisfactory on account of the difficulty of drawing tangents to the curve with accuracy.

A curve of flux densities in the air-gap may be found directly by making use of two pilot brushes separated by a distance equal to the

distance between two adjacent commutator bars. If these pilot brushes are placed on the commutator in any fixed position the voltage between them will be equal to the voltage induced in an armature coil when it is in such a position in the field that the commutator bars to which its terminals are connected are in contact with the pilot brushes. If the speed of the armature and the number of armature turns between commutator bars are known, the flux density in the air-gap may be found. By taking voltage readings with the pilot brushes in successive positions around the commutator a curve of flux densities in the air-gap may be obtained.

If potential curves are taken when the armature delivers current, the effect of the armature reaction may be studied from the field distortion produced by the load.

Procedure.—Separately excite the fields of the generator from direct-current mains, connecting a rheostat in addition to the regular field rheostat in series with the field. Connect one terminal of a suitable voltmeter to one brush of the generator and the other terminal to the pilot brush. The proper connections are shown in the following diagram. The generator should be driven by a shunt motor.

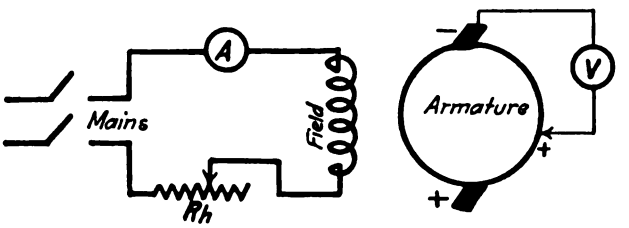


FIG. 33.

Do not open the generator field without first putting in all the resistance, because the field discharge will burn switches and may puncture the field.

Set the generator field rheostat for maximum resistance; then close the motor switch and start the motor slowly by means of its starting box. See that the voltmeter reads in the right direction. If it reads backwards, reverse it. Adjust the speed of the generator by means of the rheostat in the field of the motor. Change the motor field resistance slowly. An increase in resistance will increase the speed, a decrease will produce the reverse effect. Record the speed of the generator. Shift the main brushes until

the position which gives the maximum armature voltage is found. To obtain a reading of the armature voltage, connect the voltmeter across the armature terminals. Then adjust the field of the generator until the armature voltage equals the rated voltage of the generator. Read the field current and the position angle of the brushes. If the voltage fluctuates, it is due to a jumping of the pilot brush. A slight pressure on the pilot brush with a pencil or fountain pen should stop the fluctuation.

Move the pilot brush until a position is found where the voltmeter reads zero. The pilot brush and the generator brush to which the voltmeter is attached should now be side by side. Read the graduated scale giving the position of the pilot brush. This

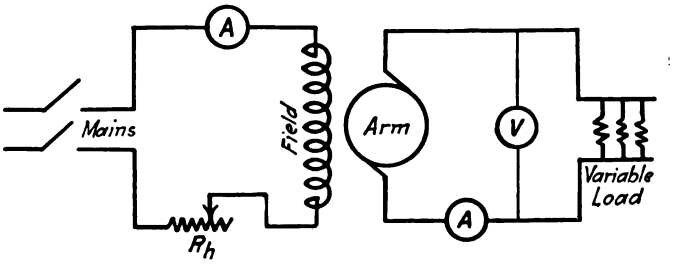


FIG. 34.

will be the zero reading, i.e., the reading from which the position of the pilot brush is to be reckoned. Now move the pilot brush in the direction of rotation of the armature, taking readings of the voltmeter for every movement of the brush of ten electrical degrees. Proceed in this way until the pilot brush has been moved from the brush to which one terminal of the voltmeter is connected, to the next brush of like polarity.

Now connect the load provided to the generator armature. An ammeter should be placed in circuit. Start the motor as before, then gradually throw on the load. If any sparking occurs the brushes should be adjusted. Record the magnitude and direction of shift required to reduce sparking to a minimum. (On a machine of recent design and with interpoles this will not be necessary.) When the load is all on, adjust the speed of the generator and then readjust load. See that the field current is the same as in the no-load run, then keeping the load and speed constant, take readings as before for every ten-degree position of the pilot brush.

If the potential about the commutator of a shunt motor is to be measured, the procedure will be essentially the same as that given for a generator. The only material difference will be that the motor will be operated as a shunt motor and no adjustment of its field will be necessary.

Results Required.—

a. Plot curve representing no-load condition as shown by Fig. 32, with volts as ordinates and positions of the pilot brush in degrees measured from the generator brush as abscissæ.

b. Plot curve similar to that in (*a*) for the full-load condition.

c. Flux distribution determined by the double pilot-brush method.

d. Determine voltage distribution around the commutator of a machine, having interpoles and a compensating winding in the pole faces, at one-half rated load.

e. Repeat (*d*) with interpole field cut out.

f. Repeat (*d*) with interpole field reversed.

g. Repeat (*d*) with compensating field cut out.

h. Repeat (*d*) with compensating field reversed.

i. Explain results in each case.

LANGSDORF, "Principles of Direct-Current Machines," 2nd Ed., p. 187.

C. R. MOORE, "Air Gap Flux Distribution in Direct-Current Machines," *Trans. A.I.E.E.*, 1912, p. 509.

12

BRUSH AND BRUSH CONTACT RESISTANCE

The voltage drop across a copper circuit carrying direct current is proportional to the current and the resistance and this drop in volts is numerically equal to the current in amperes times the resistance in ohms. The resistance of the copper is a linear function of temperature, the temperature coefficient of 100 per cent. copper at 20° C. being 0.00393. The resistance is a function of current only in so far as the temperature is influenced by the current.

Carbon has a negative temperature coefficient, consequently the resistance decreases as the temperature increases. The resistance of carbon is a function of current only for the fact that temperature is a function of current. The resistance of a hard carbon brush is greater than that of a soft carbon brush.

The contact resistance between a carbon brush and copper commutator is due to a film of air between the two surfaces, consequently this contact resistance has characteristics similar to those of the electric arc, namely—a fairly constant electromotive force associated with a resistance drop which is proportional to current. The resistance drop being small compared to the back e.m.f. makes the resultant voltage drop practically independent of the current. The apparent contact resistance, therefore, varies inversely as the current. The brush-contact drop depends also upon the hardness and composition of the brush. It is ordinarily assumed to be one volt per brush.

Under operating conditions the current density is not constant nor the same at all points of the contact surface; neither is the distribution independent of current. The distribution of the average current density depends upon the form of short-circuit curve for the coil undergoing commutation. The form of this curve depends upon many factors, i.e., resistance, reactance

voltage and commutating e.m.f. Too large a value of commutating e.m.f. gives rise to over-commutation and excessive current density at the toe [1] of the brush. Too small a value gives rise to under-commutation and excessive current density at the heel [1] of the brush. It is possible to have negative current at either the toe or heel of the brush.

A machine without interpoles suffers wide variations in commutating conditions as the load changes on account of the shifting neutral, whereas a machine having interpoles has approximately the correct commutating e.m.f. at all loads since the commutating flux is proportional to load.

Procedure.—Either a direct-current motor or a self-excited direct-current generator having well-fitting brushes and one in which the ends of the commutator bars are exposed may be used in this test. Make connections as indicated in the experiment on the type of machine used and operate at 125 per cent. load for one-half hour if possible in order to attain normal temperature conditions. Attach one terminal of a low-reading voltmeter to a brush holder and hold the other terminal against the bearing side of the brush and close to the commutator. Obtain as much contact area as possible so as to eliminate excessive contact resistance. Now vary the load from 125 per cent. rating to no-load, or one-half load if a series machine is used, taking readings of brush drop and armature current.

Procure a small spring brass or copper pilot brush which can be pressed against the ends of the commutator bars as they revolve and a point contact which can be pressed against the brush just above the commutator and thus determine brush-contact drop under operating conditions. Take readings with the pilot brush and point contact in line radially, starting at the toe and advancing one-quarter of the brush width after each reading. From the five readings thus obtained a contact-voltage curve may be plotted. Take this set of readings at 0, ½ and full-load current.

If the machine does not have interpoles, shift the brushes forward slightly and then backward taking readings at zero, ½, and at full-load current. If the machine has interpoles, cut-out the interpole winding and take readings as outlined above.

[1] The edge of the brush which makes contact with the segment is here called the toe, and the edge which breaks the contact the heel.

Results Required.—

a. Plot curve of average brush drop versus armature current.

b. Plot curve of average brush drop per inch of length versus average current density in amperes per square inch.

c. Plot curve of contact-voltage versus position of contact on brush for each set of readings and give reasons for differences.

d. Is the current density at any point proportional to contact voltage? Discuss fully.

e. What is the average brush-contact drop from no load to full load?

f. What would be the best value of resistance to use in calculations where it is desired to use a constant value of resistance instead of variable brush and brush contact resistances?

LANGSDORF, "Principles of Direct-Current Machines," 2nd Ed., p. 313.

GRAY, "Electrical Machine Design," p. 76.

"Standard Handbook for Electrical Engineers," 5th Ed. (24), 4341; (8), 39; (8), 41; PENDER, "Handbook for Electrical Engineers," p. 665.

H. F. T. ERBEN and A. H. FREEMAN, "Brush Friction and Contact Losses," *Trans. A.I.E.E.*, 1913, p. 559.

H. R. EDGECOMB and W. A. DICK, "Methods of Determining Brush Losses," *Trans. A.I.E.E.*, 1913, p. 565.

C. E. WILSON, "Commutation and Brush Loss," *Trans. A.I.E.E.*, 1913, p. 577.

B. G. LAMME, "Physical Limitation in d-c. Commutating Machinery," *Trans. A.I.E.E.*, 1915, p. 1739.

13

D-C. COMPOUND GENERATOR

The object of this experiment is to determine the external shunt and compound characteristics and magnetization curve of a compound generator. The machine used in this test may be motor or engine driven. In either case the speed of the generator will vary slightly with the load.

If for any reason a generator is to run at a speed which differs from rated speed, its voltage should be changed to correspond with the speed. In order to maintain the flux conditions for which the machine was designed, the change in voltage should be proportional to the change in speed. If the ratio of speed to voltage is not kept constant, not only will the flux be changed but the percentage compounding will also be altered. A decrease in voltage produced by a decrease in shunt field excitation will always result in an increase in the compounding and probably an increase in the tendency to spark under load.

Since the limiting value of current for any machine is determined by the I^2R loss in the conductors, the current rating of a machine cannot be increased as the voltage is reduced in order to keep the kilowatt rating constant. The current rating of a machine is not affected by any ordinary change in voltage.

The magnetization curve of a generator or motor shows the relation at constant speed between the no-load terminal voltage and the exciting current. The magnetization curve is often called an open-circuit curve or saturation curve.

Since the ampere-turns in the field are proportional to the field current and the no-load terminal voltage is proportional to the armature flux, provided the generator be driven at a constant speed, the magnetization curve really gives the relation between ampere-turns in the field and armature flux. Since speed is an element in determining the voltage, the speed at which a magnet-

ization curve is taken should always be stated. In general this should be the rated speed of the machine.

A complete magnetization curve is shown in Fig. 35. Magnetization curves are useful in comparing different types of machines. Due to the effect of residual magnetism, a magnetization curve will usually start at a point slightly above zero voltage. Should the residual magnetism be absent, the curve will start at zero.

For low values of the field current, the reluctance of the iron circuit, i.e., its resistance to the passage of magnetic lines of force, is small and nearly the entire field current is necessary to force the flux through the air-gap, which has very high magnetic reluctance as compared with the iron. The reluctance of the air-gap is constant, hence the portion of the field current necessary to force any flux through it will be proportional to the flux. If then a line be drawn tangent to the lower part of a magnetization curve, it will show for each degree of magnetization approximately how much field current is necessary to force the flux through the air-gap. For example, *ob* in Fig. 35 is such a line. For the condition represented by the voltage *V*, a field current equal to *oe* is necessary to force the flux through the whole machine. The portion *od* is required for the air-gap, *de*, for the iron.

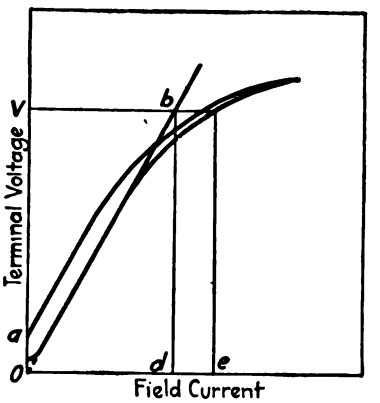


FIG. 35.

Procedure. (*a*) **Shunt Characteristic.**—Connect the generator as shown in Fig. 36, being sure to have the series coils cut out. Short-circuiting the series coils will not be sufficient since they are of very low resistance. Put all the resistance in the shunt field rheostat, *Rh*, see that the brushes are at the neutral point, and then bring the machine up to speed. If it fails to build up and come up to voltage, one of the several things mentioned under "Direct-Current Generator Connections" (page 77) may be the trouble.

Before trying to locate the fault be sure that there is not an

open circuit in the field connections, and also that the resistance in the field rheostat has been cut out. A shunt machine will not build up if it has more than a certain critical resistance in its field circuit.

The absence of a very small deflection of the voltmeter needle will indicate lack of residual magnetism. In this case current must be put through the shunt field coils from an external source of power in order to restore the magnetism.

If on closing the field circuit, the small deflection of the voltmeter which is due to residual magnetism decreases, the shunt field connection is reversed.

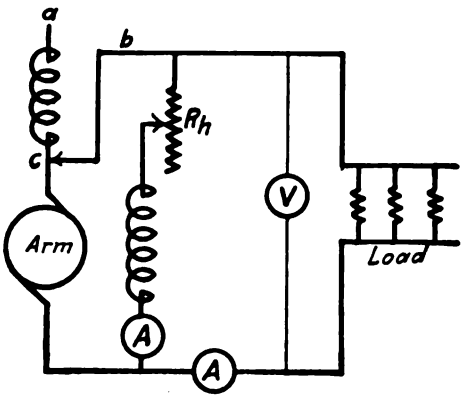


FIG. 36.

With no load on the generator adjust its terminal voltage by means of the field rheostat to the proper value for the speed at which the machine is to be run. If possible maintain speed constant at rated value. Read the speed, terminal voltage, field current and line current. The latter will be zero. Increase the load and take another set of readings. Proceed in this way until either the rated current is reached or the voltage has dropped so that no further increase in load is possible,[1] then reduce the load current to zero, taking readings.

About ten to twelve sets of readings should be taken from no load to full load and an equal number should be taken on the return to no load.

[1] Some compound generators will not deliver full-load current without their series coils.

Put all the resistance in the field circuit. If a switch is provided for the field open this, but *not until all the resistance in the field rheostat is in series with the field.*

(*b*) **Compound Characteristic.**—Connect in the series field so that it assists the shunt coil. A rapid fall of voltage when the load is applied will indicate that the series field connections are wrong. The connections are the same as in Fig. 36 except that the points *a* and *b* are connected and the connection between *b* and *c* is removed.

When the connections have been properly made adjust the no-load voltage as in the shunt characteristic and take data for the compound characteristic going from zero to full load then back to no load.

(*c*) **Magnetization Curve.**—Reduce the excitation of the generator. Then disconnect the field from the armature and separately excite it from some external source having a voltage about

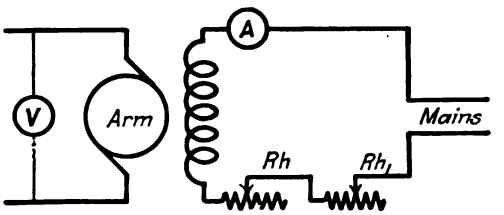


FIG. 37.

equal to the normal voltage of the generator. A large resistance equal to at least ten times the resistance of the shunt field coils should be inserted in addition to the regular field rheostat, or a drop wire used to obtain variable voltage on field. If a resistance is used it must be capable of large variation and at the same time be able to carry the field current without overheating. Such a resistance is not often at hand. Several rheostats of different resistance and current capacities will answer as well, provided care is taken to cut out the rheostats with the highest resistance and consequently smallest current-carrying capacity first. The proper connections are shown in Fig. 37, Rh_1 being an extra rheostat.

Bring the generator up to speed if it has been shut down, and take readings of voltage, field current and speed, increasing the field current from zero to a maximum and then back to zero. In

obtaining data for the rising portion of the curve, care must be taken not to increase the current by more than the desired amount and then reduce it. Such procedure will introduce loops in the curve and render it of no value. During the descending portion of the curve a similar precaution is necessary.

Results Required.—

In curves (a), (b), (c), (f) and (g) make separate curves for increasing and decreasing load. Speed characteristics should be plotted with each curve.

a. Shunt characteristic—(terminal voltage vs. line current).

b. Compound characteristic—(terminal voltage vs. line current).

c. Magnetization curve—(no-load terminal voltage vs. field current).

d. On the magnetization curve draw a line showing the field current required to force the flux through the air-gap and find the percentage of field current required for the air-gap at rated voltage.

e. Explain why shunt and compound characteristics for increasing and decreasing load do not coincide.

f. Armature characteristic—(armature current vs. field current for constant terminal voltage).

g. Compound characteristic starting at three-fourths rated voltage.

h. Armature resistance.

i. Necessary series ampere-turns for flat compounding.

j. Ampere-turns of armature reaction at full load.

k. Find ratio of shunt to series turns.

l. Determine the number of series turns per pole.

m. With what resistance must the series field be shunted in order to have 5 per cent. regulation?

n. Determine armature reaction from a short-circuit run.

o. Having the armature reaction, magnetization curve, armature resistance, etc., determine the regulation by some graphical method.

p. How does the per cent. of compounding vary with the voltage?

q. Drive a synchronous converter as a d-c. shunt generator. Place a transformer of adequate voltage, frequency and current rating across two diametrically opposite a-c. terminals. From the

mid-point of the transformer obtain the neutral. Using a load to neutral, plot each voltage to neutral vs. neutral current.

r. How does the armature reaction of a generator vary with the position of the brushes? Express in ampere turns and degrees displacement. Make measurements with full-load current in armature.

s. For a fixed brush position, how does the effect of armature reaction vary with the saturation of the field circuit? Take $\frac{E_a}{n}$ as a measure of saturation.

LANGSDORF, "Principles of Direct-Current Machines," 2nd Ed., chap. VI.
DAWES, "Electrical Engineering," vol. I, chap. X.
KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. I, p. 251.
FRANKLIN and ESTY, "Elements of Electrical Engineering," chap. VII.
"Standard Handbook for Electrical Engineering," (8), 144.
HUDSON, "Engineering Electricity," p. 43.
GRAY, "Principles and Practice of Electrical Engineering," 2nd Ed., chap. XIII.

14

PARALLEL OPERATION OF SHUNT GENERATORS

In order that two or more generators may be operated successfully in parallel, their characteristic curves must be such that the machines will divide the load in proportion to their rated outputs and at the same time be in stable equilibrium.

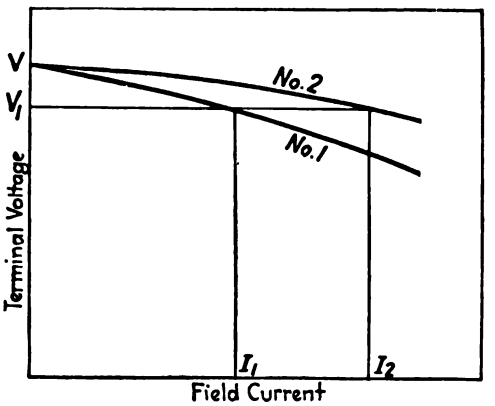


FIG. 38.

The shape of the characteristic curves of shunt machines insures the second of these conditions. Any two or more shunt generators may be run in parallel in so far as stability is concerned, but whether or not they divide the load properly will depend upon the relative slopes of their characteristics.

Any two machines when in parallel must have the same terminal voltage since their terminals are connected to the same busbars. Suppose two dissimilar shunt generators are brought to the same potential and are then put in parallel. Let the load be zero. Fig. 38 will represent the characteristics of two such machines.

The potential of both machines is the same and the current in each is zero. Let a load now be thrown in circuit. The terminal potentials of both machines will decrease but they must still be equal. If the machines are loaded until the potential has fallen to V_1, the current in machine No. 1 will be I_1; that in No. 2, I_2. The current in No. 2 increases faster than the current in machine No. 1, and if the machines were of the same size, No. 2 would be overloaded before No. 1 reached full load. It is obvious that the characteristics of the two machines must be the same if they are to share the load equally at all loads. If the machines are of different sizes their characteristics should be similar, that is, their characteristics should each show the same drop in voltage for the same fractional part of full-load current.

There is no great objection to operating shunt generators with slightly different characteristics in parallel, since the only effect will be a disproportionate division of load. This will cause no trouble so long as no machine is overloaded. Moreover, if necessary, the load may be divided properly at any output by adjusting the field rheostats.

The proper connections for the parallel operation of shunt generators are shown in Fig. 39. The voltmeter V should be arranged so that it may be connected to either machine.

Suppose machine No. 1 is running under load and it is desired to throw in machine No. 2. First bring machine No. 2 up to speed and adjust its field rheostat until the voltmeter V reads the same whether connected to the terminals of No. 2 or to the bus-bars. Be sure that the polarity of the incoming machine is the same as that of the bus-bars. If the switch S_2 is now closed, machine No. 2 will be in parallel with machine No. 1. It should, however, take no load. It may be made to take its proper share of the load by slowly increasing its field current and decreasing the field current of the other machine. By changing both fields the bus-bar voltage may be kept constant.

If the voltage of No. 2 is high, it will take load when it is put in parallel with No. 1. If the voltage is much too high, it may be considerably overloaded, and may even drive the other machine as a motor. If the voltage is too low, there will be a rush of current from No. 1 which will drive No. 2 as a motor.

To take a generator out of service, its field should be slowly weakened until the current delivered by the machine is zero. At



the same time it will be necessary to increase the field excitation of the other machine to maintain constant voltage at the bus-bars. When the current delivered has been reduced to zero, the generator may be disconnected from the bus-bars by tripping its circuit breaker and then opening its main switch or if there are no circuit breakers by simply opening the main switch.

Procedure.—Connect the generators for parallel operation as shown in Fig. 39.

Take the shunt characteristics of each machine separately, starting each characteristic at no load at the rated voltage corrected to correspond to the actual speed at which the machines are driven.

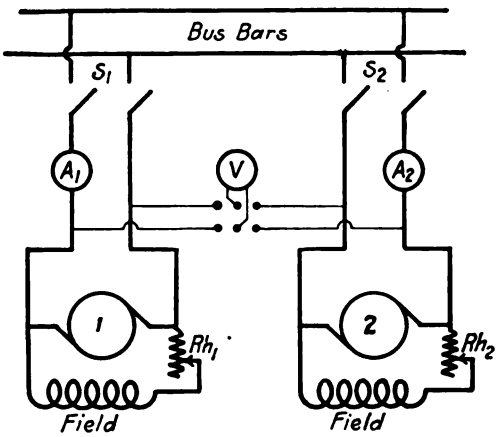


FIG. 39.

Put the generators in parallel at no load. Load the system slowly, recording the line currents, terminal voltage, and speeds for about seven or eight different loads up to full load. If the machines do not divide the load in proportion to their rated outputs, load them until either delivers its full-load current. Then take off the load and disconnect the generators from the bus-bars by opening the switches S_1 and S_2.

Now close switch S_1 and bring machine No. 1 up to full load, keeping the voltage constant by adjusting the field rheostat. Make the voltage of machine No. 2 exactly the same as the voltage of machine No. 1 and close S_2. Generator No. 2 should take no load. Now increase its field and note the effect on both the current distribution and the voltage of the system.

Reduce the current taken by No. 2 to zero, by adjusting its field rheostat and then note the effect of weakening the field of generator No. 1.

Again reduce the load of No. 2 to zero by increasing field of generator No. 1, then slowly increase the field of No. 2 and at the same time weaken the field of No. 1 so as to keep the potential of the system constant. Note the effect.

Results Required.—

a. Shunt characteristic of each machine when operated separately. Both curves should be plotted on the same sheet with external load current as abscissæ.

b. Curves of current in each machine against total current output of the machines when in parallel.

c. Determine graphically from the external characteristics the curves of machine current versus external load current.

d. Determine the load distribution obtained by paralleling the machines with the no-load terminal voltages differing by 5 per cent. of rated value.

e. Determine curves of field current in each machine versus load current for proper division of load.

f. What effect has a poor contact in one of the armature circuits on the division of load?

DAWES "Electrical Engineering," vol. I, p. 372.

HUDSON, "Engineering Electricity," p. 48.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. I, p. 264.

LANGSDORF, "Principles of Direct-Current Machines," 2nd Ed., p. 224.

GRAY, "Principles and Practice of Electrical Engineering," 2nd Ed., p. 164.

15

PARALLEL OPERATION OF COMPOUND GENERATORS

Compound generators are used to maintain constant potential at the switchboard or at some definite point on the line. For this reason, they are generally more or less overcompounded to compensate for the drop in potential between their terminals, and the point at which constant potential is to be maintained.

The parallel operation of compound generators is similar in many respects to the parallel operation of shunt machines (see page 94) but in order to insure stability one additional condition must be fulfilled. If two or more overcompounded compound generators are paralleled and one, for any reason whatsoever, takes more load, its potential will tend to rise due to the effect of its series coil. This will cause this machine to take still more current which in turn will still further increase its voltage. As a result of this accumulative effect, the machine which first starts to take a little more load will almost instantly grab all the load and in addition will tend to run the other machines as differentially compounded motors. This is, of course, not only fatal to parallel operation but also injurious to the machines unless they are properly protected by circuit breakers.

This unstable condition can be entirely prevented by paralleling the series coils as well as the machines themselves. Then, if any one machine attempts to increase its load, the increase in current divides between the series coils of all the generators inversely as the resistances of these coils. The result is that no one machine can increase its potential without also increasing the potential of the others and cannot, therefore, take load at the expense of the other generators.

The voltage characteristics of two compound generators are shown in Fig. 40. The division of load between them when in parallel, however, can not be determined as was done in the case of

the shunt generator on account of the effect of the equalizer connection. For with an equalizer in, the series field currents are determined by the total load current and the relative series field resistances and do not in any way depend upon the individual armature currents. The shape of the voltage characteristics of each machine is changed by putting in an equalizer and this change is largely dependent upon the relative series field resistances.

Suppose, for example, that the machines have the same kilowatt capacity but machine No. 1 has a higher degree of compounding. If the series field resistance of No. 1 is greater than that of No. 2, then when in parallel, the compounding of No. 1

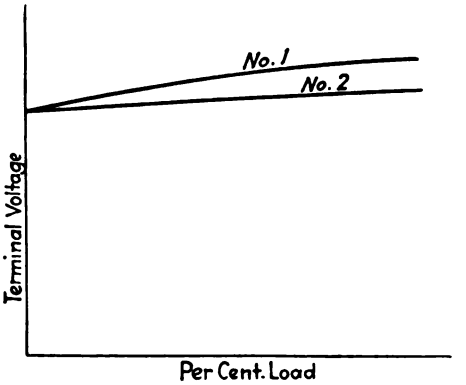


FIG. 40.

may be less than that of No. 2 due to some of the current being shifted from the field of No. 1 to that of No. 2.

The division of load between the two machines will be in proportion to the difference between their generated electromotive forces, and the armature terminal voltage, and inversely as the armature resistances for

$$I_1 = \frac{E_{a_1} - V_a}{R_{a_1}} \quad \text{and} \quad I_2 = \frac{E_{a_2} - V_a}{R_{a_2}},$$

$$\frac{I_1}{I_2} = \frac{E_{a_1} - V_a}{E_{a_2} - V_a} \cdot \frac{R_{a_2}}{R_{a_1}}.$$

The machine with the greater electromotive force, when in parallel will, for equal armature resistances, carry the greater load. As pointed out above, however, the machine with the

greater electromotive force when acting alone does not necessarily carry the greater load when in parallel because of the effect of the relative series field resistances on the compounding.

In order that the machines may divide the load properly, their characteristics must be similar and in addition the resistances of their series coils must be inversely proportional to their ratings.

Fig. 41 is a plot showing the distribution of load between two generators when in parallel.

In order that no current shall flow in the equalizer, i.e., in the connection which parallels the series coils (see Fig. 42), the drop of potential through the series coils of all the machines must be equal when each series coil carries the rated current of its machine.

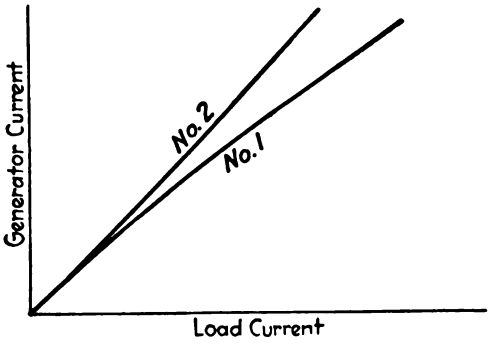


FIG. 41.

If R_{s_1}, R_{s_2}, etc., represent the resistances of the series coils of several generators and I_1, I_2, etc., represent their rated currents, the following relation must hold if the current in the equalizer is to be zero:

$$I_1 R_{s_1} = I_2 R_{s_2} = I_3 R_{s_3} = \text{etc.},$$

or

$$\frac{1}{R_{s_1}} : \frac{1}{R_{s_2}} : \frac{1}{R_{s_3}} : \text{etc.} = I_1 : I_2 : I_3 : \text{etc.}$$

for two machines

$$\frac{R_{s_1}}{R_{s_2}} = \frac{I_2}{I_1}.$$

If the machines are of the same size R_{s_1} should equal R_{s_2}.

Any two compound generators in parallel will be stable provided there is an equalizer. They cannot, however, be made to share the

load properly without current flowing in the equalizer unless their characteristics are similar and the resistances of their series coils are inversely proportional to their rated current outputs.

The proper connections for the parallel operation of two generators are shown in Fig. 42. These connections can be extended for any number of generators.

Suppose generator No. 1 is in operation, switches S_1 and S_2 being closed. To throw in generator No. 2, first bring it up to speed, then close the equalizer switches S_3 and S_3' and adjust the voltage of generator No. 2 until it is approximately the same as

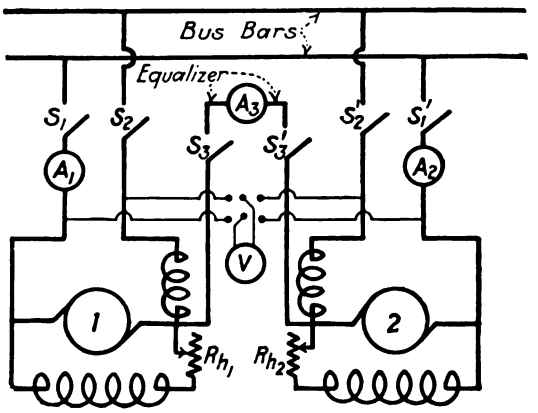


FIG. 42.

that of generator No. 1. Close the switch S_2' connecting the series coil of the incoming machine to line. This will cause a drop in the line voltage due to shunting part of the current from the series coil of the other generator by the series coil of generator No. 2. This drop should be corrected by adjusting the shunt field of No. 1. Now adjust the voltage of the incoming generator, No. 2, until it is the same as that of the bus-bars, then close switch S_1'. The generators will now be in parallel but generator No. 2 will have no load. There will be, however, current in the series coil of generator No. 2 supplied through the equalizer from the other machine. Generator No. 2 may now be made to take its proper share of the load by slowly increasing its shunt field current. The shunt field current of the other generator should also be changed to keep the line voltage constant. To take the generator out of circuit, the load

on it should be reduced to zero and the switches S_1', S_2', S_3', and S_3 opened in the order named. The line voltage is adjusted by field rheostat Rh_1.

The equalizer switch for any generator must always be closed before both terminals of the generator are connected to the bus-bars, and must never be opened until at least one terminal of the generator has been disconnected from the bus.

The switches S_1' and S_2' may be closed together and may be replaced by a single double-pole switch. The switches S_1', S_2' and S_3' may even be combined into a single three-pole switch provided the blade of S_3' is slightly wider than the blades of S_2' and S_1' so that the equalizer connection shall be made first when the three-pole switch is closed.

The ammeters must be placed so as to indicate the actual output of the generators, and, therefore, must be placed so that their readings will not be influenced by any current which may be flowing through the equalizer. The best position for the ammeters is shown in the diagram of connections, Fig. 42. If, for any reason, they are placed in the main containing the series coil, they must be placed between the armature and the equalizer connection.

Procedure.—Connect the two generators as in Fig. 42, being sure that the equalizer and series coils are properly arranged. Bring both generators up to speed and voltage and test the polarities of each to see that they are the same.

Then take the compound characteristic of each machine separately, starting each characteristic at the voltage at which the machines are to be run when in parallel.

Put the generators in parallel at no load. Increase the load on the system until either generator delivers full-load current. Record the current output of each generator, the line voltage, the equalizer current, and occasionally the speeds as the load is increased.

Reduce the load until it is a little less than the full load of one generator, then take one machine out of service.

Following the directions already given put this generator back in parallel with the one already loaded. Notice the effect on the voltage of the system and the current in the equalizer, when the switch connecting the series coil to the line is closed.

Try shifting the load from one machine to the other: first, by adjusting the rheostat in the field of one machine alone, then, by adjusting both field rheostats.

Results Required.—

a. Plot the compound and speed characteristic of each machine alone using generator current as abscissæ.

b. Plot the current of each machine when in parallel against the total current. See Fig. 41.

c. Plot terminal voltage of system against line current of one machine as its load is removed by adjusting its rheostat only. Each machine to be operating at one-half load originally.

d. Two unlike compound generators are to be operated in parallel. What resistance should be placed in series with one of the series field windings to cause the load to divide at full load in proportion to the machine ratings. Make runs on each machine from which the resistance may be calculated. Check results by running the machines in parallel and adjusting for proper division of load at full load.

HUDSON, "Engineering Electricity," p. 49.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. I, p. 266.

LANGSDORF, "Principles of Direct-Current Machines," 2nd Ed., p. 226.

DAWES, "Electrical Engineering," vol. I, p. 374.

GRAY, "Principles and Practice of Electrical Engineering," 2nd Ed., p. 166.

16

CONSTANT-CURRENT, VARIABLE-SPEED GENERATORS

There are two types of constant-current, variable-speed generators; the Rosenberg or four-brush generator and the so-called third-brush generator. Both of these will, within limits, deliver constant current to a load of constant back electromotive force, as for instance a storage battery. The Rosenberg generator develops an e.m.f. the direction of which is independent of the direction of rotation, while for a given field connection the third-brush generator will operate satisfactorily in only one direction. The Rosenberg generator is widely used for train lighting and the third-brush for automobile lighting.

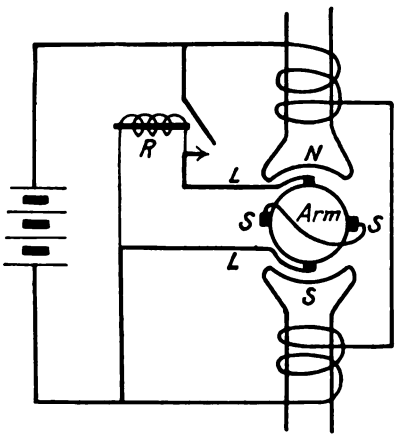


FIG. 43.

The schematic diagram of connections of the Rosenberg generator is shown in Fig. 43.

For successful operation it must be connected to a storage battery, which also excites the field. The axis of the load brushes *LL* is along the polar instead of the interpolar axis as in a normal machine. These brushes are connected to the battery by means of a relay *R* which does not pull in until the voltage across *LL* is slightly greater than that of the battery. This prevents battery discharge when the generator runs at slow speed or is at rest.

In the interpolar axis are two additional brushes *SS* which are short-circuited. Rotation of the armature through the flux, due to the main field, causes a current to flow through the short-circuited brushes *SS*. For right-hand rotation a m.m.f. will be set up

to the left, due to the short-circuit current. The design of the magnetic circuit is such that the effect of this cross m.m.f. is large compared to that of the main field. Rotation of the armature through this cross field will cause a voltage across the main brushes and the current resulting therefrom produces a direct demagnetizing action on the main field.

As the speed increases the voltage across *SS* tends to increase, which means more current in *SS*, more cross flux, more voltage across main brushes, more load current, and consequently greater direct demagnetization of the main field. This greater demagnetizing action means less voltage in circuit *SS* and consequently

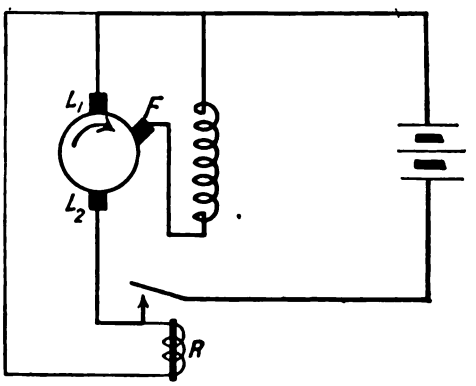


FIG. 44.

less load current. Since these effects tend to neutralize the current in *SS* and consequently the current delivered from *LL* (since this voltage is produced by the cross field *SS*) will remain practically constant over a wide variation of speed. The value of this current may be adjusted by adjusting the field rheostat.

A schematic diagram of the third-brush generator is shown in Fig. 44.

The third-brush generator has its armature connected to a source of constant potential, as does the Rosenberg generator. In this case, however, the brushes L_1L_2 are placed in the interpolar axis and the brush F is placed at an intermediate point.

Assume the machine to be operating and delivering current to the battery. An increase in speed will increase V_t which tends to increase the current and consequently armature reaction. For a generator this means that the flux axis is shifted ahead, reducing

the net flux in the zone L_1F and consequently reducing the voltage across L_1F, the field current, and the main flux. By proper design these two effects may be made to balance, and sensibly constant current may be delivered over a wide range of speed. The current delivered may be varied by changing the position of F.

In case the direction of rotation is reversed the brush F should go on the other side of the commutator. As this type of machine is generally used for automobile lighting this shift is seldom necessary.

Procedure.—(*a*) Run the Rosenberg generator at a variable speed with a storage battery across its terminals. Measure the load current, terminal voltage, field current and short-circuit current.

Next run at constant maximum speed varying the field current taking the same readings.

(*b*). Run the third-brush generator with a storage battery of proper voltage across its terminals. Measure the load current, terminal voltage, field current and speed. Next make a run at constant maximum speed and vary the position of the brush F, taking the same readings and the angular displacement of the brush from L_1.

Results Required.—

a. For the Rosenberg generator:
1. Curves of load current, terminal voltage, field current and short-circuit current against speed.
2. Curves of load current, terminal voltage and short-circuit current against field current for constant maximum speed.

b. For the third-brush generator:
1. Curves of load current, terminal voltage and field current against speed.
2. Curves of load current and terminal voltage against brush displacement from L_1.
3. What displacement from L_1 should be used to charge a 60-ampere hour battery at the eight-hour rate?

FRANK CONRAD, "Electrical Equipment of Gasoline Automobiles," *Trans. A.I.E.E.*, 1913, p. 2043.

S. R. BERGMAN, "A Direct-Current Generator for Constant Potential at Variable Speed," *Trans. A.I.E.E.*, 1918, p. 1405.

LANGSDORF, "Principles of Direct-current Machines," 2nd Ed., p. 425 and p. 434.

17

STARTING BOXES FOR DIRECT-CURRENT MOTORS

The armature current of a shunt motor $I_a = \frac{V_t - E_a}{R_a}$ where V_t is the impressed voltage, measured at the armature terminals and E_a is the generated voltage or back electromotive force of the armature. R_a is the armature resistance and I_a the armature current. The back electromotive force E_a is proportional to the speed and flux and its direction is such as to oppose the flow of current in the armature.

$$E_a = \frac{p\phi Zn}{a \times 60 \times 10^8},$$

where p = number of poles;

ϕ = flux per pole in maxwells;

Z = number of armature inductors;

n = speed in revolutions per minute;

a = number of paths in parallel through the armature.

At the time of starting E_a is zero. Under this condition the armature current equals the impressed voltage divided by the armature resistance. The full-load I_aR_a drop in a moderate-sized motor is approximately 5 per cent. of the rated voltage of the motor. If the armature of such a machine were placed across mains of rated voltage without external resistance, the initial current would tend to be twenty times normal full-load current, since a voltage twenty times the normal full-load armature resistance drop is impressed. This means the copper loss, $I_a^2R_a$, would be 400 times its full-load value.

To limit the current to a safe value during the starting period a variable resistance is connected in series with the armature.

A starting current of 1.5 full-load current is satisfactory. If R_1 is the resistance of the starting box, the total resistance in series with the motor will be R_1+R_a. $R_1+R_a=\frac{V_t}{1.5I_a'}$, where I_a' is the full-load value of armature. The current will develop a torque $=K\phi I_a$ which will accelerate the motor and develop an induced voltage E_a. This induced voltage will reduce the current I_a to $\frac{V_t-E_a}{R_1+R_a}$ and consequently the torque in the same proportion. E_a will continue to increase until I_a and thence torque is reduced to equal exactly the reactive torque of the load. When this condition is reached the motor will not accelerate further and will continue to run at that speed as long as conditions remain unchanged.

A starting box should be designed to start a motor under full-load torque. Consequently I_a will not be assumed to fall below I_a'. Then with the resistance R_1 in series $V_t=1\frac{1}{2}I_a'(R_1+R_a)$ at starting and $V_t=I_a'(R_1+R_a)+E_{a_1}$ when equilibrium has been reached.

$E_{a_1}=\frac{1}{3}V_t$ and $n_1=\frac{1}{3}$ rated speed n. Then $\frac{2}{3}V_t$ is used up in resistance drop. That means that we may decrease the resistance in the box to R_2 such that $R_2+R_a=\frac{\frac{2}{3}V_t}{1.5I_a'}$,

$V_t=1\frac{1}{2}I_a'(R_2+R_a)+E_{a_1}$ at instant when external resistance is reduced to R_2. When equilibrium is established,

$$V_t=I_a'(R_2+R_a)+E_{a_2},$$

$$\tfrac{2}{3}V_t=\tfrac{3}{2}I_a'(R_2+R_a),$$

$$V_t=\tfrac{4}{9}V_t+E_{a_2},$$

$$E_{a_2}=\tfrac{5}{9}V_t,$$

$$n_2=\tfrac{5}{9}n.$$

Then $\frac{4}{9}V_t$ is used up in resistance drop. This may be continued until all the steps are computed, which will be when R_n+R_a equals or is less than R_a which is of course the last step when the armature is placed across the line and runs as a motor at normal speed.

It should be noted also that when this method is used, the speed for a definite load has been calculated for each point on the starting box. If the resistors in the starting box would carry rated current

continuously the box could be used for speed control. It would, however, be very inefficient due to the waste of power in heating the resistance. In the normal starting box the resistance is not designed to carry the current continuously, but only for a short period equal perhaps to twice or three times the normal starting period.

The number of steps with the values of the resistances may be determined very simply by graphical means providing the armature resistance is known. Assuming the permissible starting current to be $1\frac{1}{2}$ times rated full-load current we can calculate the total resistance necessary for the first point. This includes the armature resistance. See Fig. 45.

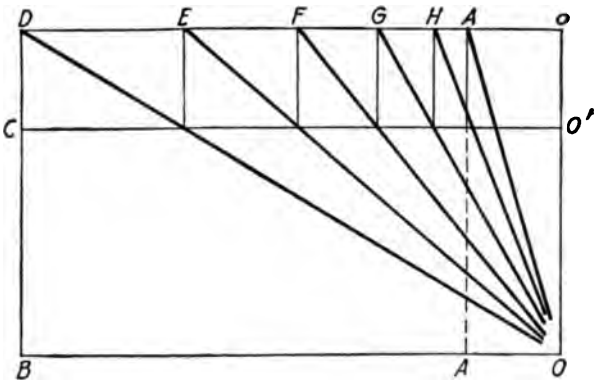


FIG. 45.

Lay off OB equal to this resistance where OA equals the armature resistance and AB the total resistance of the box. Let BD be the maximum permissible value of the current and BC the current necessary to accelerate full load. Connect O and D. As the motor accelerates the current drops until it reaches the full-load value BC. If the total resistance is reduced to oE, the current will again rise to BD and will fall to BC. By continuing this process until the entire starting box resistance is cut out, the exact number of steps required and the resistance of each step may be readily determined.

In the case of a series motor E_a increases at the instant when resistance is cut out, consequently a graphical solution similar to that given for a shunt motor does not apply.

Procedure.—If a shunt motor is assigned, measure the armature resistance by passing full-load current through the armature and measuring the voltage drop. See Fig. 27. In case a series motor is assigned measure the resistance of the series field also, and take the magnetization curve.

Results Required.—

a. Amount of resistance which must be placed in series with the armature of the motor on starting at full load. (Starting current not to be more than 1.5 times rated full-load current.)

b. Amount of this resistance which may be included in the first step without causing the line current to exceed 1½ times its full-load value, the motor operating at full-load torque.

c. Number of steps necessary before this resistance is entirely cut out.

d. Could this rheostat be connected in the line of a shunt motor instead of in the armature?

e. Calculate the length and size of wire which would be used in a rheostat for the motor tested. (Assume *IaIa* wire.)

f. Draw a complete diagram of a starting box such as is used in practice and explain the purpose of its various parts.

g. Design a starting box for the series motor assigned.

H. D. JAMES, "Industrial Controller with Particular Reference to the Control of the Direct-Current Shunt Motor," *Trans. A.I.E.E.*, 1917, p. 253.

"Standard Handbook," 5th Ed., (15) 504.

PENDER, "Handbook for Electrical Engineers," p. 1369.

18

SHUNT-MOTOR LOAD CHARACTERISTICS

The curves which are important for showing the operating characteristics of any shunt motor are indicated in Fig. 46. In order to obtain these curves it is necessary to measure the electrical input, speed and mechanical output of the motor under different loads. The simplest way of determining the mechanical output

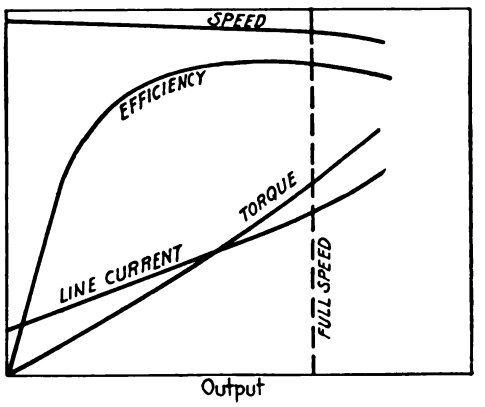


FIG. 46.

is by means of one of the many forms of brake. This is the method to be adopted in this experiment.

The armature current in a motor is given by the relation $I_a = \frac{V_t - E_a}{R_a}$ where V_t and E_a are respectively the terminal voltage as measured at the armature terminals and the generated voltage or back electromotive force. The back electromotive force is proportional to the speed and flux, and the direction is such that it tends to prevent the flow of current in the armature. $E_a = Z'n\phi$,

$$Z' = \frac{pZ}{a \times 10^8 \times 60},$$

where p = number of poles;

Z = number of armature conductors;

a = number of paths in parallel through the armature.

Z' is obviously constant for a given machine and its use in the above equation will give E_a in volts when n and ϕ are in revolutions per minute and maxwells or lines respectively.

If the speed is zero, as when starting, E_a will also be zero. Under this condition the armature current will be equal to the impressed voltage divided by the armature resistance. The full load I_aR_a drop in a motor of moderate size is usually about 5 per cent. of the rated voltage of the motor. If full voltage were impressed at starting on a motor with a 5 per cent. full-load armature-resistance drop, the armature current, i.e., the starting current, would be twenty times the full-load armature current of the motor and the armature $I_a^2R_a$ or copper loss would be 400 times its full-load value.

To limit the current to a safe value during the starting period a variable resistance is connected in series with the armature. This resistance is gradually reduced to zero as the motor speeds up. The starting rheostat is designed to carry approximately 150 per cent. rated armature current for a few seconds only and must not under any circumstances be made to carry this current continuously. The reasons for the short time rating are that (*a*) the rheostat is used intermittently and has ample time to cool off between periods of use, (*b*) it would be too bulky if designed for continuous service, and (*c*) it would cost too much.

The two types of starting boxes for shunt motors that are in general use are, namely: "The Three-point Box" and "The Four-point Box." The diagram of the three-point box is shown in Fig. 47 and that of the four-point box in Fig. 50. It will be noted that the hold-up magnet of the three-point box is excited by the field current and is, therefore, styled the no-field release. This is to prevent the motor from racing if the field circuit is accidentally opened. The hold-up magnet of the four-point box is connected in series with a large resistance and is excited directly from the mains, and therefore releases the arm of the starting box whenever the voltage fails. This is to prevent a motor being seriously injured if the voltage fails momentarily, thus allowing the motor to slow down and then suddenly having full voltage reimpressed

upon it. The arm of a three-point box does not immediately return to the starting position when the voltage fails because the generated electromotive force of rotation excites the field and hold-up magnet as the machine slows down.

Procedure.—Connect the motor as shown in Fig. 47 in which a three-point or no-field release starting box is shown. If a four-point box is provided, connect as in Fig. 50, page 122, except that there will be no field to put in series with armature. See that the ammeters are short-circuited, then close the main switch and bring the motor up to speed. The motor should be started under no load. Be sure that it rotates in the proper direction. If it starts in the wrong direction open the main switch and reverse the connections of either the armature or the field.

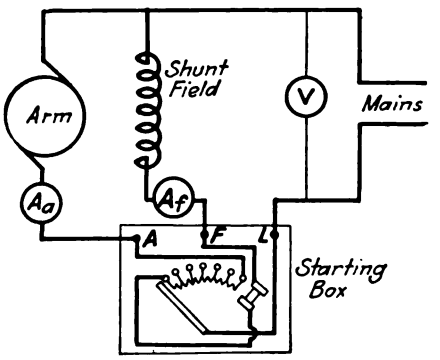


FIG. 47.

Never stop a motor, even if it has not attained full speed, by allowing the arm on the starting box to return to the starting position. The arm must not be allowed to return to this position until after the main switch is open. Failure to observe this rule always results in burning and finally in the destruction of the contacts on the starting box.

The approximate value of the full-load current of any motor may be found by dividing its rated output by the voltage and the assumed efficiency at full load. A table giving the efficiencies which may be expected for machines of various sizes is given on page 28.

After the motor is up to speed, load it until it takes about 25 per cent. more than its full-load current. Allow the motor to run at this load for at least ten minutes in order to warm up, then take

several sets of readings of line current, field current, line voltage, speed, balance, and weights if any are used in connection with the brake.

The speed will be obtained by observing the number of revolutions made by the motor in a minute. Be sure that the balance arm is kept in a horizontal position, and also that water is kept in the brake drum, when a friction brake is used. This water will evaporate quite rapidly and will have to be occasionally replenished. Care should be taken not to wet the friction band about the brake drum.

After completing the readings for about 25 per cent. overload, reduce the load slightly and take another set. About eight sets of readings should be taken at different outputs between 25 per cent. overload and no load. At the end of the run determine the zero reading of the brake. (See pages 21 and 22.)

In order to find the distribution of losses in the motor it will be necessary to measure its armature and field circuit resistances.

Disconnect the motor, then connect the armature in series with an ammeter and a considerable resistance to the mains. In determining the size of this series resistance, the resistance of the armature may be neglected. If a current of I amperes is desired and the voltage of the circuit is V, the necessary resistance will be

$$\frac{V}{I} = R \text{ ohms.}$$

NOTE: Be sure that the rheostat used in measuring the armature resistance has not only sufficient resistance but also has ample current-carrying capacity. A starting box can never be used on account of this latter requirement. Measure the current through the armature and the voltage drop across its terminals, with the armature in several different positions, being sure of using a current of from 50 to 100 per cent. full-load values.

Since the armature resistance is small a voltmeter having a low-range scale will be necessary. Before using this low-range scale be sure to try the voltage on the high-range scale, in order to prevent injury to the instrument. As soon as a reading has been taken disconnect the low-voltage scale. See Chapter II for the calculation of the low-range voltmeter.

The resistance of the shunt field circuit may be determined from data taken in load run.

If for any reason it is necessary to determine the resistance of the field with the motor at rest it is measured the same way as armature resistance except that no series resistance will be required and the low-voltage scale on the voltmeter will not be necessary. A lower range ammeter, however, will be required. See Chapter II for its calculation.

Precaution.—*When measuring the field and armature resistances be sure to disconnect the voltmeter before breaking the circuit. Failure to do this will result in serious damage to the voltmeter from the field discharge. In large machines precautions have to be taken when the field circuit is broken to prevent injury to the field itself.*

Before leaving the laboratory make a sketch of the connections and the form of brake employed. Also be sure that data are tabulated and all columns are headed with meter numbers, zero readings and units used.

The output of the machine may be determined as follows:

$$\text{Output in h-p.} = \frac{2\pi nT}{33{,}000},$$

where n is the revolutions per minute made by the motor and T is the torque computed from the brake reading.

$$\text{Efficiency in per cent} = \eta = \frac{\text{h-p. output} \times 746}{I_L V_t} \times 100,$$

where I_L is the sum of armature and field currents and V_t is the line voltage.

The total watts lost in the machine $= P_t =$ Input $-$ Output

$$= \frac{\text{Full-load output}}{\text{Full-load Eff. (from curves)}} - \text{Full-load output.}$$

The loss in the field is I^2R_f. Since the field current is found by dividing the voltage V_t by the field resistance the field loss becomes

$$I_f V_t = I_f^2 R_f = \frac{V_t^2}{R_f^2} R_f = \frac{V_t^2}{R_f} = P_f.$$

The armature copper loss, $I_a^2 R_a = P_a$ represents the loss in power due to heating the armature winding by the passage of the current. Obtain full-load line current from curves and obtain $I_a = I_L - I_f$.

$P_t - (P_a + P_f)$ gives the remaining losses, i.e., friction, windage and core losses, which are known as stray power, P_{SP}.

Results Required.—

a. Curve of efficiency against horse-power output.

b. Curve of line current against horse-power output.

c. Curve of torque against horse-power output.

d. Curve of speed against horse-power output.

e. Distribution of losses at full load expressed in per cent. of input.

f. Determine the magnetization curve of the motor by running the armature on reduced voltage and varying the field over as great a range as possible. This need not be done at constant speed provided the proper corrections are applied.

g. How do the stray-power losses as calculated in (*e*) compare with the no-load input to the armature? Should the results be the same? Explain.

h. Calculate the change in speed in going from no load to full load assuming armature reaction to be zero. How does this result compare with the measured change in speed? Calculate the per cent. change in speed due to armature reaction.

i. What would be the approximate rating of this motor if it were operated on one-half rated voltage?

j. What resistance must be connected in series with the armature to reduce the speed by 10 per cent. at full-load torque? What will be the efficiency under this condition?

k. Calculate the rise in temperature in armature winding from change in resistance, using A. I. E. E. formula. (See page 16.)

l. Calculate the rise in temperature in field coils using the same method as in *k*.

m. Percentage speed regulation at full load.

n. Why will slight temporary fluctuations in the impressed voltage cause comparatively large variations in the line current?

o. How would you reverse the direction of rotation of a shunt motor?

p. Explain method employed in measuring armature resistance when rise in temperature is desired.

LANGSDORF, "Principles of Direct-Current Machines," 2nd Ed., chap. VII.

DAWES, "Electrical Engineering," vol. I, p. 321.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. I, p. 278.

GRAY, "Principles and Practice of Electrical Engineering," 2nd Ed. chap. XV.

19

SERIES-MOTOR LOAD CHARACTERISTICS

(Before studying this experiment read that on the "Shunt Motor Load Characteristics")

This test is to obtain the characteristic curves of a series motor and is to cover the same ground as the test on the shunt motor.

The shunt motor is essentially a constant speed motor and is generally used for driving stationary apparatus where good speed regulation is required and where the motor does not have to start under any great load. When subjected to heavy load at starting a series motor is far superior to a shunt motor. A series motor is particularly adapted to work requiring good effort under widely varying speeds. It is for this reason that series motors are universally used for traction purposes, electric hoists and the like.

If a shunt motor were used for electric traction, it would require large current at starting, as well as on grades where it would tend to maintain the same speed as on a level. The series motor, on the other hand, exerts good torque at starting without excessive current, and on grades slows down and does its work at a moderate speed and current. This particular property of a series motor is due to the fact that the flux is a function of the load current.

The speed of a motor is inversely proportional to its field strength and nearly proportional to the voltage at the terminals of its armature. The torque or turning moment exerted by the armature is proportional to the product of the field strength and the armature current.

Since the field and armature of a series motor carry the same current, hence when this current is large, as in starting or on grades, the torque will be large and the speed low. As the motor speeds up, the increase in back electromotive force will decrease the current and cause the field to weaken. Therefore the speed of a series motor increases rapidly with decrease in load. Due to this increase

in speed, sufficient load must always be maintained to prevent dangerously high speed or racing. Fuses are no protection since the excessive speed occurs under light load and small current.

The function of a starting box is the same whether it be used in connection with a series or shunt motor, although its arrangement may be somewhat different. The small magnet which holds the movable arm in the running position on a starting box for a shunt motor must be either in series with the field or connected through resistance across the mains. For a series motor this magnet must be either in the main circuit where it will act as an underload release, or shunted across the mains as in the case of the four-point box of a shunt motor.

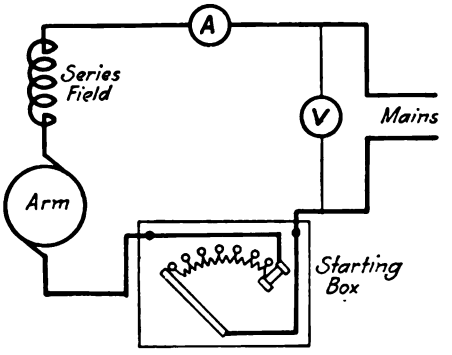


FIG. 48.

A series motor must always be started under sufficient load torque to prevent racing, but on the contrary a shunt motor may be started under no load.

Procedure.—See if the motor used in this experiment is provided with a circuit breaker which opens the circuit in case the current falls below a safe minimum.

Inspect the motor assigned and notice the type of brake used for getting the output and also the kind of starting box employed.

Connect up the motor as shown in Fig. 48.

NOTE.—In case a starting box has its hold-up magnet across the line instead of in the main circuit, another connection to the starting box will be needed.

First close the overload circuit breaker and underload circuit breaker, if one is provided, then close the main switch and with a moderate load on the motor bring it slowly up to speed. The underload circuit breaker will not stay closed until sufficient load

is applied to motor. Keep the ammeter well short-circuited while starting.

Put about twenty-five per cent. overload on the motor and allow it to run ten or fifteen minutes, then proceed according to the directions given under the Shunt Motor. The load, however, in the case of the series motor should not, of course, be reduced to zero. The underload release should operate when the maximum safe speed is reached, which in no case should be more than 175 per cent. of rated full-load speed.

At the end of the run shut down the motor and measure the resistance of the armature and field separately. *Since the resistances of both the armature and the field of a series motor are low, a considerable resistance must be placed in series with each when measuring*

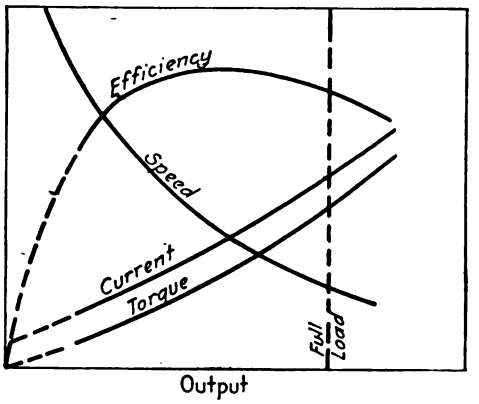


FIG. 49.

its resistance. Before measuring these resistances read the directions for measuring armature resistance under the Shunt Motor. Be sure to disconnect the voltmeter before breaking the circuit.

Record the necessary dimensions of the brake and its zero reading as well as the numbers and zero readings of all the instruments used in the test.

The total watts lost in the machine $= P_t$

$$= \text{Input} - \text{Output}$$

$$= \frac{\text{Full-load output}}{\text{Full-load Eff. (from curves)}} - \text{Full-load output}$$

P_a = watts lost in armature = I^2(full-load current from curves)R_a

P_f = watts lost in field = I^2 (full-load current from curves) R_f,

P_{SP} = total losses minus the above I^2R losses = $P_t - P_a - P_f$ = stray-power loss.

Results Required.—

a. Curve of efficiency against horse-power output.

b. Curve of current against horse-power output.

c. Curve of torque against horse-power output.

d. Curve of speed against horse-power output.

e. Distribution of losses at full load expressed in per cent. of input.

f. Determine the temperature rise in the field by measuring its resistance before and after the test. See page 15.

g. Separately excite the field with full-load rated current; impress line voltage across the armature and measure its input. How does this compare with the stray power loss calculated in (*e*)? Explain any discrepancies.

h. How does the rating vary with impressed voltage?

i. Determine the magnetization curve by separately exciting the field and running the armature on varying voltage.

j. Assuming no-load stray-power to be equal to that determined as in run (*g*), calculate the no-load current and no-load speed when running with rated voltage impressed.

k. If this motor is used for hoisting work, what resistance must be connected across its terminals when the bucket is being lowered in order that it will lower one-half load at speed corresponding to one-half load. Must the field be reversed?

l. Calculate the rise in temperature in the armature from the change in resistance using the A. I. E. E. formula. See page 16.

m. How do the components of stray power in a series motor change with load? Compare with the same losses in a shunt motor.

n. Calculate the change in speed from half load to full load assuming the flux directly proportional to the current. Compare with the measured results and explain the causes for any difference.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. I, p. 286.

LANGSDORF, "Principles of Direct-Current Machines," 2nd Ed., p. 250.

DAWES, "Electrical Engineering," vol. I, p. 324.

GRAY, "Principles and Practice of Electrical Engineering," 2nd Ed., p. 90.

20

COMPOUND-MOTOR LOAD CHARACTERISTICS

Cumulatively-Compounded Motor.—There are certain classes of work which require motors that will develop good torque at starting and which will operate with only moderate changes of speed under ordinary variations of load.

An ideal motor for this purpose would combine the starting qualities of a series motor with the running properties of a shunt motor. Such a machine is obviously impossible, but something approaching it may be obtained by putting a series or compound winding on the field of a shunt motor and connecting this compound winding in series with the armature in such a way that it assists the shunt coils. A motor arranged in this way will develop a large torque while starting, due to the increase in the strength of its field produced by the heavy starting current in the series winding. Under running conditions the effect of the series coil will be comparatively small and the speed regulation will be fairly good. The speed regulation, however, cannot be so good as that of the shunt motor, neither can the starting torque be so good as that of the series motor. The good qualities of each type of motor must be sacrificed to a very considerable degree in order that the motor, to a limited extent, may possess the qualities of both.

A motor with a compound winding connected so as to aid its shunt field is called a cumulatively-compounded motor. Such motors are largely used for elevator service.

Differentially-Compounded Motor.—The speed regulation of a shunt motor is sufficiently good for most purposes, but in certain cases as, for example, in textile mills where a slight variation in speed may affect the work a differentially-compounded motor may be used.

A properly designed differentially-compounded motor will run at nearly constant speed from no load to full load.

The speed of a shunt motor falls off slightly with increasing load

but it may be maintained constant by weakening its field as the load comes on. This may be accomplished manually by slightly increasing the resistance of a rheostat placed in the shunt field, but may be done automatically by differentially compounding the motor.

If, in addition to the shunt winding, a few turns of heavy wire are wound on the field, and these turns are connected in series with the armature or line, any change in the current in the armature will affect the field and consequently the speed of the motor. If these turns are connected so as to act in opposition to the shunt field winding, any increase in the load on the motor will weaken the field and increase the speed over that which the motor would have

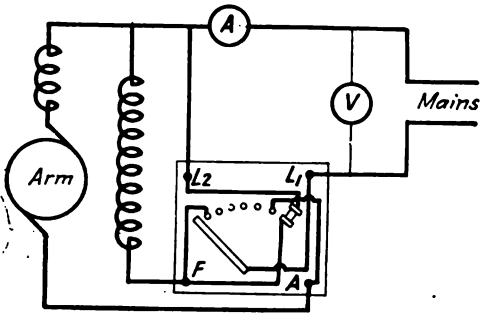


FIG. 50.

if the shunt coils alone were used. If the number of turns is properly adjusted the speed will remain practically constant from no load to full load. If too many series turns are used the speed will rise; if too few the speed will fall. In order to adjust the effect of the series field, a shunt is often provided by means of which the current through the series turns may be varied. If a shunt is used it is usually adjusted by the manufacturer before the motor leaves the shop.

Since the weakening of the field by the series coils may be considerable when the motor is started or is heavily overloaded, care must be taken in handling a motor of this type. A differentially-compounded motor, should always be started slowly and should be well protected from heavy overloads.

Procedure.—Inspect the motor assigned for this experiment and from its name-plate rating determine what instruments will be required. Note the form of brake and starting box used, then connect up as shown in Fig. 50. In case a three-point box is

used connect up as in Fig. 47, page 113, putting series field in series with armature.

Take readings for motor curves, following the directions given in the procedures of the shunt and the series motor experiments.

Data for three sets of curves should be taken, the first set with the series coils out; the second, with the series coils connected cumulatively; and the third, with the series coils connected differentially and shunted in case a shunt is provided. The series coils should not be shunted during the cumulative run.

Results Required.—

a. Curve of efficiency and output as a shunt motor.

b. Curve of current and output as a shunt motor.

c. Curve of torque and output as a shunt motor.

d. Curve of speed and output as a shunt motor.

e. Repeat (*a*) to (*d*) inclusive for motor connected cumulatively.

f. Repeat (*a*) to (*d*) inclusive for motor connected differentially.

g. Calculate the percentage distribution of losses at full load in each case and compare.

h. Ratio of series to shunt turns. Determine by first operating at full-load current and speed with the motor differentially connected, and then operate at the same current and speed with the motor cumulatively connected.

i. Compounding expressed as the ratio of ampere turns in the series and shunt coils at full load.

j. Determine the percentage increase in the series field turns which would be necessary to produce a full-load torque of $1\frac{1}{4}$ times normal full-load value.

k. How many series turns are required for zero speed regulation?

l. With what resistance should the series field be shunted in order to obtain zero speed regulation with the motor connected differentially?

m. What is the percentage change in speed due to armature reaction?

LANGSDORF, "Principles of Direct-Current Machines," 2nd Ed., p. 252.

DAWES, "Electrical Engineering," vol. I, p. 328.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. I, p. 287.

GRAY, "Principles and Practice of Electrical Engineering," 2nd Ed., p. 93.

21

ADJUSTABLE-SPEED INTERPOLE-MOTOR LOAD CHARACTERISTICS

The speed of any shunt motor is given by

$$n = \frac{V_t - I_a R_a}{\phi Z'},$$

where V_t is the impressed voltage, I_a and R_a the armature current and armature resistance respectively, and ϕ the armature flux. Z' is a constant depending upon the armature winding. See page 111.

The speed may be varied, as may readily be seen from the formula, by changing either R_a or ϕ. Changing R_a results in very poor economy. If the speed is reduced to half by increasing R_a, approximately 50 per cent of the power supplied to the motor will be wasted in this resistance.

The variation of speed which can be obtained by altering ϕ is limited in the ordinary shunt motor to about 25 per cent. on account of the sparking which occurs when a motor is run with a weak field. This sparking is caused by the field distortion produced by the armature reaction acting on a weak field, making it impossible to maintain the proper flux at the point of commutation to neutralize the effect of the self-induction in the short-circuited armature coils.

This difficulty is overcome in shunt motors of the interpole type by putting small magnetic poles midway between the regular poles. These auxiliary poles are connected in series with the armature so as to oppose the field due to armature reaction and maintain the field necessary for commutation. Since these auxiliary poles are in series with the armature, their strength will vary with the armature current. Consequently the field for commutation varies in proportion to the current load on the motor. Motors of this type, if properly designed, will develop their rated output

over a very considerable range of speed, will carry overload and will run in either direction sparklessly without any change in brush position.

The controller for a motor of the interpole type is usually a combination of an ordinary starting box and a field rheostat. The first few notches on the controller correspond to a starting box and are not running positions. A movement of the controller handle beyond the first running position inserts resistance in the field circuit, weakening the field and causing the motor to speed up. The controller may also be so arranged that the direction of rotation

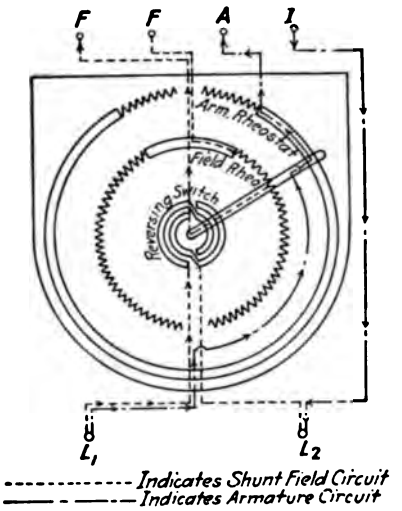


FIG. 51.

of the motor can be reversed. The diagram of such a controller is shown in Fig. 51.

Procedure.—The object of this experiment is to obtain curves similar to those called for under the Shunt Motor.

Two sets of readings are to be taken, one with the controller set for minimum speed, and one with the controller set for maximum speed. Take data at slow speed, allowing the motor to run at least ten minutes at full load before recording any data. The speed should be measured by means of the voltage generated by a magneto attached to the motor shaft or by some form of direct reading tachometer. The magneto with its voltmeter, or tachom-

eter if used, must be calibrated at the beginning of the test over the range of speed at which the motor is to be operated.

The connections for the test are shown in Fig. 52. In making these connections the interpoles must be connected in such a way that the field produced by them opposes that caused by armature reaction. To test whether the interpoles are connected properly, start the motor and bring it up to full speed, i.e., the highest speed at which it is designed to run, then apply full load. If sparking occurs shut down and reverse the interpole connections. If a compensating pole face winding is used it must also be tested for proper connections.

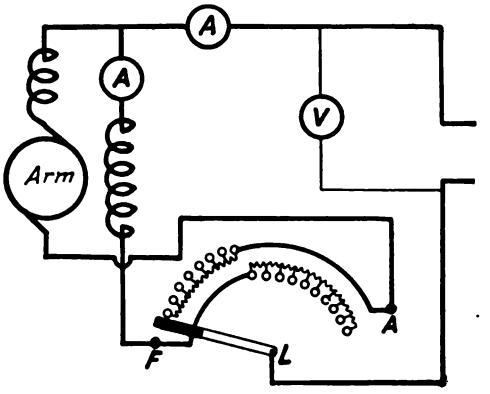


FIG. 52.

The controller may or may not open the main circuit. If it does not, the main switch must be used. Instead of measuring the field resistance, which should include that resistance in the controller which is in series with the field, an ammeter should be put in the field circuit during the run to indicate the field current. The reading of this ammeter multiplied by the line voltage will give the I^2R loss in the field circuit. This I^2R loss will vary with the speed setting of field rheostat.

At the end of the test measure the armature resistance, the resistance of the interpoles, and the resistance of the compensating field. All these resistances will be low so that a rheostat must be put in series with them when measuring them.

Results Required.—

Curves (*a*) to (*d*) inclusive are to be both for controller in minimum and maximum speed positions.

a. Efficiency and output.

b. Line current and output.

c Torque and output.

d. Speed and output.

e. Calculate distribution of losses at full load in per cent. of input for both minimum and maximum speeds and explain why they differ.

f. Omit interpoles and operate with full-load current taking readings of speed and torque. Plot speed versus torque.

g. Replace interpoles and repeat (*f*), measuring the electrical input also. Compare the curves of (*f*) and (*g*) and explain.

h. From data taken in (*g*) plot efficiency against speed.

i. From data taken in (*g*) plot field current against speed.

j. Determine the flux distribution at full load with and without the interpoles in circuit.

k. Do interpoles affect the flux distortion caused by the cross magnetizing action of the armature?

l. Explain why the breakers may be thrown out by suddenly increasing the field strength.

m. Why does the speed decrease so rapidly when the field is suddenly increased at no-load?

n. What is the object of having a compensating winding in the pole faces of some variable speed motors?

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. I, p. 291.

22

METHODS OF SPEED VARIATION OF A SHUNT MOTOR

The current through the armature of a shunt motor is equal to the difference between the impressed voltage and the back electromotive force of the armature, divided by the armature resistance. This back electromotive force, or armature-induced voltage as it is called, is caused by the armature conductors cutting across the lines of force of the field.

If V_t is the impressed voltage and E_a is the armature induced voltage, the current in the armature is given by

$$I_a = \frac{V_t - E_a}{R_a}, \quad \ldots\ldots\ldots \quad (1)$$

where R_a is the armature resistance. It follows from this expression that the armature-induced voltage of a motor is equal to the impressed voltage minus the product of the armature current and the armature resistance,

$$E_a = V_t - I_a R_a. \quad \ldots\ldots\ldots \quad (2)$$

According to Ohm's Law, $I_a R_a$ represents the drop of potential through the armature due to the armature current, I_a, flowing through the armature resistance, R_a.

The electromotive force generated by the movement of a conductor across a magnetic field is proportional to the strength of the field and to the speed at which the conductor moves. Since the armature of a motor consists simply of a series of conductors revolving in a magnetic field, it follows that the back electromotive force set up in it as it revolves, that is, its armature induced voltage, must be proportional to the speed with which its conductors move and to the strength of field in which they revolve.

The armature induced voltage is then given by

$$E_a = Z' \phi n, \quad \ldots\ldots\ldots \quad (3)$$

where Z' is a constant, depending upon the armature winding, ϕ, the strength of the magnetic field in which the armature revolves, and n the speed of revolution.

Combining this with equation (2)

$$E_a = Z'\phi n = V_t - I_a R_a. \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Solving for n

$$n = \frac{V_t - I_a R_a}{Z'\phi}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

There are three variables in this expression for speed, V_t, I_a, and ϕ.

If a shunt motor is run on constant potential mains, V_t will be constant. Since the field is connected across constant potential mains, ϕ which depends upon the field current will also be constant except in so far as it may be influenced by the current in the armature reacting on the field. The only thing which can change the speed under the above conditions is the armature current. This will increase as the motor is loaded, causing the term $I_a R_a$ to increase and the speed to diminish.

It is readily seen from what has been said that if the change in speed from no load to full load is to be small the term $I_a R_a$ must be small. The only way this can be made small for a given size of motor is to make the armature resistance as small as possible. This is always done.

Suppose the resistance of the armature of a 230-volt motor is 0.3 ohm and its full-load armature current is 50 amperes, the speed at full load will be, from equation (5),

$$n = \frac{230 - 15}{Z'\phi}.$$

At no load $I_a R_a$ will be very small, not more than 1.0 volt. If V_t is constant the field current will be constant and ϕ will vary but little. The principal change in speed which occurs must be due to the change in the numerator of the above equation. This will be

$$15 - 1 = 14,$$

or

$$\frac{14}{230} = 6.1 \text{ per cent.}$$

It is readily seen from this why a shunt motor does not race when the load is thrown off.

It is often necessary to change the speed of a shunt motor in order that it may be used for some special piece of work. This may be done in two ways, either by changing the field strength by variation of the field current, or by putting resistance into the armature circuit. This latter is equivalent to increasing the armature resistance.

Variation of ϕ.—If ϕ is changed, the speed of the motor will be changed in the inverse ratio, i.e., an increase in ϕ will produce a corresponding decrease in speed, and vice versa. Since ϕ is dependent upon the field current, an increase in this current will cause the motor to slow down, while a decrease will cause it to speed up. The difference in speed from no load to full load, will not be changed since variation in flux does not affect the term I_aR_a.

Most motors are built to run without a field rheostat. In this case it will be impossible to slow the motor down by increasing the field current. It may be speeded up, however, by putting resistance in the field circuit and in this way decreasing the field current. It is seldom safe to increase the speed of a motor more than 25 per cent. above its rated value and even if it were, it probably could not be done on account of the tendency of an ordinary motor without commutating poles to spark under load, if run with a weak field.

Variation of Resistance placed in the Armature Circuit.—From equation (5) when I_a is small, as under light loads, a change in R_a will have very little effect on the speed but if the motor is loaded so that I_a is large, a small change in R_a will make a very marked change in speed.

Suppose it is desired to reduce the speed 50 per cent. at full-load current. In order to do this

$$\frac{I_aR_a}{V_t}100 \text{ must} = 50,$$

or

$$I_aR_a = \frac{V_t}{2}.$$

The full-load current was 50 amperes. Solving the above equation for R_a and substituting the values of I_a and V_t

$$R_a = \frac{V_t}{2I_a} = \frac{230}{2\times 50} = 2.3 \text{ ohms.}^1$$

It is impossible to increase the armature resistance R_a, but adding resistance to the armature circuit will have the same effect.

The speed regulation in this case will be very poor. Suppose the load is thrown off. The armature current to run a motor of this size at no load will be about four amperes. For no load I_aR_a will be $4\times 2.3 = 9.2$ volts, while the value of the voltage drop for full-load current will be $50\times 2.3 = 115$ volts.

The percentage change of speed from no load up to full-load current will be

$$\frac{115-9.2}{230} = 45 \text{ per cent.,}$$

as against 6.1 per cent. under normal conditions. Aside from the poor speed regulation this method gives, it is very uneconomical, since it involves a large amount of energy wasted in the resistance placed in series with the armature. In the case assumed, half of the energy supplied to the motor armature is wasted.

Variation of Voltage.—There is still another method by which the speed of a motor may be reduced. This is by varying the voltage V_t applied to the armature circuit. This may be done by supplying current to the armature from storage batteries, but these are often not available.

If the motor is run on a three-wire system, its speed may be reduced to approximately one-half by supplying current to its armature at half voltage, as shown in Fig. 53.

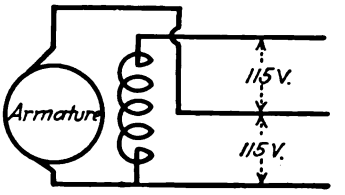


FIG. 53.

This method is economical, and at the same time gives good speed regulation. For example: Suppose the motor used in the previous examples has its armature put on half voltage by con-

[1] In these equations R_a may be considered to be the total resistance through which the current I_a flows.

necting it between the neutral and one outside wire of the three-wire system. V_t will be 115 and the speed regulation will be

$$\frac{14}{115} = 12.2 \text{ per cent.},$$

as compared with 45 per cent. by the previous method. Aside from the better speed regulation this last method involves no waste of energy in resistance, as does the former.

If this last method is used, precautions must be taken to prevent injury to the field when its circuit is opened. If the machine is small there will be little danger. If it is large, however, a high resistance shunt should be placed about the field terminals to take the discharge from the magnetic field when the field circuit is opened. Ordinarily, when the circuit of a shunt motor is opened, the armature acts as a generator supplying current to its field causing the field current to decrease slowly as the machine slows down.

Procedure.—An ordinary shunt motor, or preferably a motor with commutating poles will be used for this experiment. Load will be applied either by a friction brake or by belting the motor to a generator which may be loaded with a resistance load. A rheostat for varying the motor speed by armature resistance and a suitable field rheostat should be provided in addition to the ordinary starting box.

Cut out all the resistance in the field rheostat. Make sure that the brushes are set properly and then start the motor. Adjust the field rheostat to give the maximum speed at which it is safe to operate the motor. Ask what this speed is, unless an adjustable speed interpole motor is used, in which case the maximum speed should be found on the name plate.

Load the motor, taking about eight readings of current and speed between no load and full load. The speed can best be obtained by means of some form of direct-reading tachometer.

Throw off the load and adjust the motor field for minimum speed and repeat the above set of readings.

A third run should be made with the motor field set for the maximum speed, but with enough resistance inserted in the armature circuit to give the same speed at full-load current that the motor had at full load in the second run. Throw off the load leaving the rheostats unchanged and take a third set of readings

of speed and current as load is applied. If the speed of a motor is to be reduced by reducing the armature voltage, it will be impossible to still maintain the same horse-power output since this would involve an increase in the motor current beyond its rated value and consequently overheat the motor. Take about eight sets of readings between no-load and full-load current.

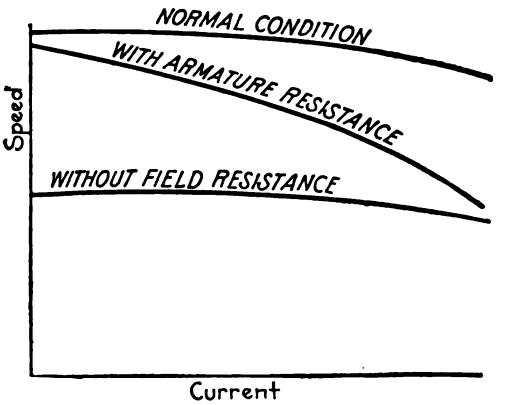


FIG. 54.

Results Required.—

a. Speed against current (minimum field).

b. Speed against current (maximum field).

c. Speed against current (armature resistance control).

d. Speed against current for armature across half voltage if a 230-volt machine is used.

DAWES, "Electrical Engineering," vol. I, p. 339.

LANGSDORF, "Principles of Direct-Current Machines," 2nd Ed. p. 258.

H. WARD LEONARD, "Speed Regulation of Electric Motors," *Trans. A.I.E.E.*, 1896, p. 377.

23

EFFICIENCY BY THE STRAY-POWER METHOD

The general expression for the efficiency of any piece of apparatus is the ratio of its output to its input. Since the difference between the input and the output must be equal to the sum of the losses, the equation for efficiency may be written

$$\eta = \frac{\text{Output}}{\text{Output} + \Sigma \text{ losses}}, \quad \ldots \ldots \quad (1)$$

or

$$\eta = \frac{\text{Input} - \Sigma \text{ losses}}{\text{Input}}. \quad \ldots \ldots \quad (2)$$

The calculation of efficiency by the measurement of the losses has distinct advantages in both accuracy and ease of manipulation. If the total losses are 10 per cent. of the input, and an error of 5 per cent. be made in their determination, the error introduced in the efficiency will be of the order of magnitude of 0.5 per cent., whereas an error of 5 per cent. in the determination of either input or output by direct measurement will cause nearly 5 per cent. error in the efficiency. The power saved by this method of determining efficiency is also an important consideration.

The losses in a motor or generator at a given speed are fixed by the voltage at its terminals and the current in its windings. The losses in a motor are therefore fixed by its electrical input: those of a generator are fixed by its electrical output. Equation (2) is therefore used for a motor. Equation (1) is for a generator. By the use of equations (1) and (2) respectively for a generator

and motor, all the terms entering into the equations for efficiency can be expressed in electrical units.

The total losses in a generator or motor may be divided as follows:

Copper losses: (*a*) in the field.
(*b*) in the armature.

Iron losses: (*a*) Hysteresis losses in the armature core and the field-pole faces.
(*b*) Eddy-current losses in the armature core, the field-pole faces and other metal.
The iron losses in the pole faces are due to the pulsations of flux caused by the armature teeth as they sweep by the poles.

Mechanical losses: (*a*) Bearing and brush friction.
(*b*) Windage.

The sum of the iron losses and the mechanical losses is called the stray-power or rotational loss, and while the components are capable of separate determination only with considerable labor, their sum is very easily found.

The copper loss in the armature for any particular armature current may be computed from a measured value of armature resistance. If the armature loss is determined in this way the heating loss due to the short-circuit current in the coils undergoing commutation is neglected. Since the number of coils being commutated at any time is a small fraction of the total number in circuit, this loss may be neglected. The copper loss in the field may be computed for any load and speed from the field current for the given load. As an approximation, the field current measured when the stray-power loss is being found may be used in computing the field copper loss in case it is impossible to measure or calculate the actual field current for the given load.

Method of Finding the Stray Power.—In a given machine the iron losses depend *only* upon the speed and armature flux, and the mechanical losses depend *only* upon the speed. Therefore, the stray-power loss of a dynamo for a *given speed* and *flux* is inde-

pendent of how the dynamo operates, i.e., whether as motor or generator or whether under load or at no load. This statement is not strictly correct as it neglects the effect on core loss of the distortion of the armature flux produced by the load. The electrical input to the *armature* of any motor at no load is equal to the armature copper loss due to the no-load current I_{a_0} plus the stray-power loss for the speed and flux under which it is running.

$$V_{t_0} I_{a_0} = I_{a_0}^2 R_a + P_{SP},$$

or

$$P_{SP} = V_{t_0} I_{a_0} - I_{a_0}^2 R_a, \quad \ldots\ldots \quad (3)$$

where V_{t_0} = voltage at terminals of armature, I_{a_0} = current through armature under the condition of no load and R_a = armature resistance.

If then any given machine, either motor or generator, can be operated at no load at the speed and armature flux it would have under any given load, its stray-power loss will be the same as the stray-power loss it would have if actually operated under the load. Therefore, if the speed and armature flux of any machine when operating at *no load* as a *motor* are made equal, respectively, to the speed and armature flux for any load condition, the stray-power loss for that condition can be found by equation (3).

Obviously the speed may be determined by any form of direct-reading tachometer or if necessary by an ordinary revolution counter. The armature flux cannot be determined by any direct measurement, but armature *induced* voltage, E_a, which is proportional to it at any fixed speed, can be found.

Since

$$E_a = Z' n \phi, \quad \phi = \frac{E_a}{Z' n},$$

where ϕ is the armature flux and n is the speed in revolutions per minute. Z' is a constant the significance of which is given on page 111. Therefore, at any fixed speed the induced armature voltage E_a is a direct measure of armature flux. To make the no-load stray power equal to the stray power under any given load it is

therefore merely necessary to reproduce the *load speed* and *the load armature induced voltage* at no load.

For a motor

$$E_a = V_t - I_a R_a, \quad \ldots \ldots \quad (4)$$

For a generator,

$$E_a = V_t + I_a R_a, \quad \ldots \ldots \quad (5)$$

where V_t and I_a are, respectively, the armature terminal voltage and the armature current under load conditions. The proper value of armature induced voltage at which to determine the stray power of a machine may be found from equations (4) or (5).

When a machine is running at no load as a motor the measured voltage at its armature terminals is practically equal to its induced armature voltage, since the $I_{a_0}R_a$ drop at no load is small. The two voltages may be assumed equal except in the case of small machines, 1 kw. or less.

To calculate the efficiency of a shunt generator from data obtained at no load use equation (1), which may be put in the following form:

$$\eta = \frac{V_t I_L}{V_t I_L + (I_L + I_f)^2 R_a + V_t I_f + P_{SP}}, \quad \ldots \quad (6)$$

where V_t and R_a have the same meaning as in equations (4) and (5). $I_L = I_a - I_f$ = line current for assumed load, P_{SP} = stray-power loss calculated by the use of equation (3) from data taken with the machine running at no load as a motor with its speed and armature voltage made equal to the values they would have under the load conditions for which the efficiency is to be found. The second and third terms of the denominator are the armature and field copper losses respectively, whose values are readily found when I_f is known.

I_f should be the load field current. This will be somewhat larger than the field current used in determining the stray-power due to the absence of armature reaction at no load. If no specific data are at hand regarding the field current under load conditions,

it may be assumed to be 10 per cent. greater at full load than the field current used in finding the stray-power.

For a motor

$$\eta = \frac{V_t I_L - (I_L - I_f)^2 R_a - V_t I_f - P_{SP}}{V_t I_L} \quad . \quad . \quad . \quad . \quad (7)$$

where the symbols have the same meaning as in equation (6).

The voltage V_t in the efficiency equations (6) and (7) is not the same as V_{t_0}. It is the rated terminal voltage or the voltage at which the machine under test is assumed to operate. V_{t_0} is the terminal voltage used in finding the stray-power and will be different, since $V_{t_0} = V_t - I_a R_a + I_{a_0} R_a$.

Procedure.—Measure the resistance of the armature circuit of the machine to be tested. This will include the resistance of the brushes. Since there is a marked change in the brush contact

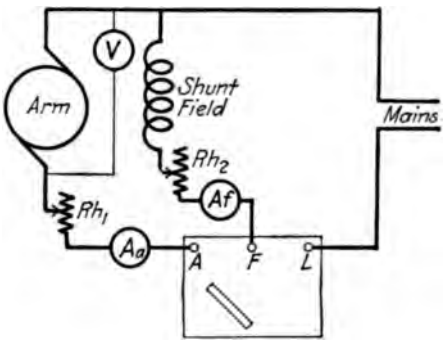


FIG. 55.

resistance with change in current density especially at low current densities, the resistance of the armature circuit should be measured using not less than three-quarters full-load current. Calculate the induced armature voltage for full-load using either equation (4) or (5) according to whether a motor or generator is to be tested. For this calculation it will be sufficiently accurate to assume the full-load armature current equal to the line current at full-load. Use the name-plate data for the full-load speed.

Connect the machine as a motor to mains of proper voltage. See Fig. 55. The rheostat Rh_2 changes the field current and therefore changes both the armature flux and the speed. The

other rheostat, Rh_1, changes only the voltage impressed on the armature circuit and hence only affects the speed. Be sure both these rheostats have sufficient resistance and current-carrying capacity.

Cut out all the resistance in Rh_1 and Rh_2 and bring the motor up to speed. Calibrate the speedometer at two or three points near the speed desired and find its constant. Make the armature voltage equal to its full-load value, as found from equation (4) or (5), by means of the rheostat Rh_1. When making this adjustment it will be sufficiently accurate in most cases to assume the voltage at the terminals of armature and the armature induced voltage equal at no load. Having adjusted the armature voltage by means of the rheostat Rh_1, make the speed equal to its rated value using rheostat Rh_2. This second adjustment may change the armature current enough to appreciably alter the drop through the rheostat Rh_1 and hence change the voltage across the terminals of the armature. If this occurs a second adjustment of both rheostats and possibly a third adjustment of them may be necessary. When the adjustments for speed and voltage have been properly made take three or four sets of readings of all instruments and of the speed. If the rheostats are not changed in the order suggested above a great deal of time will probably be wasted unnecessarily in making the adjustments for speed and voltage.

Results Required.—

a. Calculate the full-load efficiency from the data obtained.

b. Explain the advantages and disadvantages of this method of determining efficiency, and compare its accuracy with that of other methods.

c. Determine the curve of stray-power versus load current for rated voltage impressed on the motor.

d. Determine the curve of stray-power at rated speed and rated terminal voltage versus load current.

e. What is the per cent. change in stray-power in going from no load to full load?

f. Determine a curve of stray-power versus speed for constant rated flux. Assume 10 per cent. armature reaction at full load.

g. Using data taken in (*f*) calculate the efficiency curve as a motor.

h. Assuming speed and voltage constant, machine separately excited and 10 per cent. armature reaction at full load, take data to determine the efficiency curve as a generator.

i. Calculate the pulley torque developed when this machine draws rated current from mains of rated voltage and runs at rated speed.

j. Why does the armature current fluctuate badly in this test?

k. Calculate at what per cent. of full load this machine will have maximum efficiency.

HUDSON, "Engineering Electricity," p. 64.

LANGSDORF, "Principles of Direct-Current Machines," 2nd Ed., p. 375.

DAWES, "Electrical Engineering," vol. I, p. 361.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. I, p. 305.

E. I. CHUTE and W. BRADSHAW, "Sources of Error in the Efficiency Determination of Rotating Electric Machines," *Trans. A.I.E.E.*, 1913, p. 551. See Exp. 26 on Separation of Losses.

GRAY, "Principles and Practice of Electrical Engineering," 2nd. Ed. p. 95.

24

ELECTRICAL SUPPLY OF LOSSES

In the ordinary stray-power method of determining the efficiency of a direct-current generator or motor, the stray-power loss is measured with the machine running at no load as a motor. The method of Electrical Supply of Losses determines the loss under actual load conditions. Two disadvantages are that the method requires two identical machines and also requires that they be connected by a mechanical coupling.

When two rigidly coupled motors are operating on the same mains, the division of the mechanical load may be varied by changing the field rheostats; the motor with the weaker field taking the greater load.

If the machines are identical and have equal field excitations both will act as motors and will take equal amounts of power from the mains. If the field of one is increased, the induced voltage of this machine will increase and may be made greater than the terminal voltage of the system. Under this condition this machine will act as a generator and will deliver electrical power to the mains. To supply this power the other machine, which still acts as a motor, must slow down slightly. This causes a decrease in its induced voltage and allows it to take sufficient power from the mains to drive the machine which is acting as a generator. The total power taken by the system from the mains is equal to the difference between the electrical input to the motor and the electrical output of the generator. This difference is equal to the total mechanical and electrical losses in the system. If instead of increasing the field of one machine the field of the other is weakened, a similar effect is produced except that in this case the increase in the induced voltage of the machine which acts as a generator is now due to the increase in the speed of the system. By adjusting both the rheostats it is, therefore, possible to make

the set run at any desired speed and any particular load on either the generator or motor.

Since the output of the generator armature is equal to the input to the motor armature minus the total losses in the two armatures, the motor will carry a greater load than the generator. Should the generator efficiency at full load be desired the motor must be inspected frequently to make sure that it does not overheat. There is obviously no danger of overheating when the motor is being tested at full load.

This method of testing is economical because a large percentage of the motor output is eventually returned to the motor by the generator; hence the term "Pump-Back Method" is sometimes used in place of "Electrical Supply of Losses." All the individual copper losses and the combined stray-power loss are readily determined. It is impossible, by this method, to determine the individual stray-power losses without making certain assumptions. Since the speeds are equal the difference in stray-power in the two machines is due to a difference in flux. The fluxes are proportional to the armature voltages for equal speeds. The core-loss component of the stray-power of most machines is approximately proportional to the 1.7 power of the flux for any fixed speed. Since the machines used in this test have the same ratings and have equal speeds, their core losses are approximately in the ratio of the 1.7 power of the ratio of their armature voltages. The mechanical losses are equal since the speeds are equal. Since the division of the stray-power losses between mechanical losses and core losses is not known, the correct division of the total stray-power losses of the system between the two machines cannot be made. However, since the difference between the armature voltages of the two machines is not great, a sufficiently accurate division of the total stray-power loss may be obtained by assuming that the individual stray-power losses are proportional to the armature voltages.

After the stray-power and the copper losses of the machine under test have been determined, the efficiency may be derived by the usual formula involving losses and input or output.

Procedure.—To determine motor efficiency connect the machines as shown in Fig. 56. The circuits are so arranged that ammeter A_L indicates the current required to supply the stray-power losses and the armature copper losses of both machines.

Ammeter A_m gives the motor line current and A_{f_m} the motor field current. The efficiency of the generator is not required so its field is separately excited and need not be measured.

With S_1 open and minimum resistance in the field of the machine used as a motor, close the breakers and switches S and S_2 and start the motor by means of the starting box. If the motor does not start with the handle on the second or third notch, the connections should be carefully checked. If it attempts to rotate in the wrong direction, open the switch S and reverse the motor field connections.

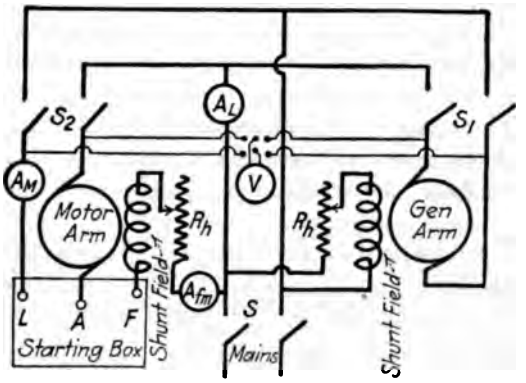


FIG. 56.

Bring the motor up to its rated speed by slowly weakening the field. Adjust the generator voltage until it is equal to the motor voltage, and of the same polarity with respect to the mains, then close switch S_1. This puts the two machines in parallel. If the voltage is properly adjusted, no current should flow in the armature of the generator.

The motor can be loaded by slowly increasing the generator field and at the same time weakening the field of the motor in order to keep the speed of the system constant. Load the system until the motor ammeter, A_m, indicates full-load current.

Allow the machines to run until the conditions become reasonably constant. Five or six hours would not be too long in an actual test, but here ten or fifteen minutes will have to suffice, then take several readings of all the instruments, viz., A_L, A_{f_m}, A_m and V. The speed of the system should also be recorded.

When the above readings have been taken, shut the system down by first taking the load off the generator, by carefully weakening its field, then opening the switch S_1, and finally opening the switch S.

The resistance of both armatures must now be measured, using the drop-in-potential method. These ought to be measured with the armatures in a number of different positions and if possible with full-load current.

The efficiency of either machine as a generator may be calculated by loading as above and measuring the field current of the machine acting as a generator.

Let I_L, I_m, I_{f_m} and V represent the readings of the instruments A_L, A_m, A_{f_m} and V, respectively, when the motor takes full-load current.

VI_L will be equal to all the losses in the system with the exception of the heating or I^2R losses in the fields.

The total stray power is then given by

$$P_{SP}=VI_L-(I_m-I_{f_m})^2R_{a_m}-(I_m-I_{f_m}-I_L)^2R_{a_g},$$

where R_{a_g} and R_{a_m} are the generator and motor armature resistances respectively.

The induced armature voltage of the motor is

$$E_{a_m}=V-(I_m-I_{f_m})R_{a_m}.$$

The induced armature voltage of the generator is

$$E_{a_g}=V+(I_m-I_{f_m}-I_L)R_{a_g}.$$

The stray power of the motor is equal to

$$\text{Total } P_{SP}\times\frac{E_{a_m}}{E_{a_g}+E_{a_m}}.$$

The efficiency of the motor will be its input minus all its losses divided by its input. The losses will be its stray power, the heating loss in its armature, and the heating loss in its field.

$$\eta=\frac{VI_m-(I_m-I_{f_m})^2R_{a_m}-I_{f_m}V-P_{SP_m}}{VI_m},$$

Results Required.--

a. Armature resistance of both machines.

b. Full-load efficiency of machine acting as motor.

c. Full-load efficiency of machine acting as generator.

d. Distribution of losses in motor at full load expressed in per cent. of input.

e. Distribution of losses in generator at full load expressed in per cent. of input.

f. Efficiency curve as a motor, points taken at each quarter load to 25 per cent. overload.

g. Efficiency curve as a generator, points taken at each quarter load to full load.

h. Compare the advantages and disadvantages of this method over the Stray-Power Method as to accuracy, practicability and ease of manipulation.

i. By means of a voltage inserted in the line connecting the two armatures test the machines under exactly similar conditions as regards flux and speed and compare results obtained with those of the usual method.

j. Why does the line current fluctuate so badly in this test?

k. How does the efficiency of a generator when determined by the electrical supply of losses compare with the efficiency as determined by the stray-power method? Plot curves of efficiency versus output for both methods.

KARAPETOFF, "Experimental Electrical Engineering" 2nd Ed., vol. I, p. 328.

DAWES, "Electrical Engineering," vol. I, p. 365.

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MECHANICAL SUPPLY OF LOSSES

In the electrical supply of losses method (Experiment 24) the losses in the two armatures were supplied electrically from the mains. The sum of these losses was indicated by the product of ammeter and voltmeter readings. If now we disconnect the two direct-connected armatures from the mains and drive the machines mechanically at the same speed we are supplying all the losses mechanically. Under this condition both the motor and the generator will carry the same armature current.

$$E_{a_g} = V_t + I_a R_{a_g}$$

and

$$E_{a_m} = V_t - I_a R_{a_m}.$$

The total input may be measured by determining the electrical input to the driving motor armature and subtracting the armature copper loss, the stray-power and the belt loss. Call this loss P_s. The copper loss in the generator and motor will be $I_a^2 R_{a_g}$ and $I_a^2 R_{a_m}$ respectively. Subtracting the sum of these from P_t gives the total stray-power. This may be divided between the two machines in proportion to the armature induced voltage as in the electrical supply of losses method. The components of stray-power may also be determined separately as described later.

This method possesses the advantages over the pump-back method in that the efficiency of one machine may be tested at any load as a generator while the other machine will be operating as a motor at the same armature current and may be tested simultaneously. By changing the field excitation the efficiency of the motor may be found as a generator and vice versa.

Procedure.—Separately excite two direct-connected machines and bring them up to speed by the auxiliary motor. The input to the two machines is the total stray-power loss. If both fields are

opened the total input is the friction and windage of the two machines which may be assumed to divide equally between the two machines. If now one field is closed the increase in motor input is the eddy-current and hysteresis loss in that machine. Now open this field and close that of the other machine measuring input.

If variable speed runs are made under any of the foregoing conditions a plot of the losses involved as a function of speed may be obtained.

With both fields closed bring voltages of each machine to rated value, when the two armatures may be placed in parallel. No current will flow. The field of one machine should be increased.

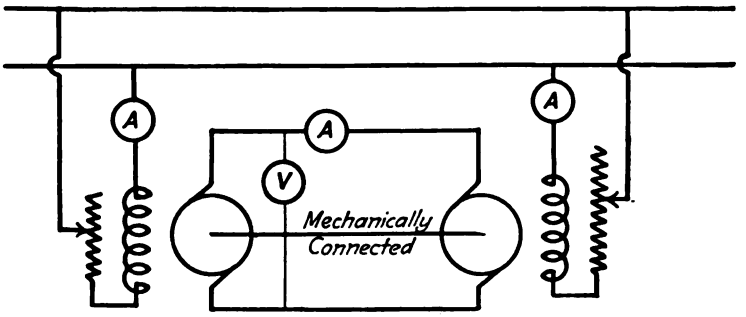


FIG. 57.

This machine will then become a generator. The field of the other should be reduced to maintain constant voltage. In this way the load current may be varied over any desired range.

Results Required.—

a. Friction and windage loss of each machine plotted against speed.

b. Friction and windage loss of each machine at rated speed.

c. Eddy-current and hysteresis loss of each machine plotted against speed for rated voltage.

d. Eddy-current and hysteresis loss of each machine at rated speed and voltage.

e. Copper loss in each machine as a function of load current.

f. Total losses in each machine as a function of load current at rated speed.

g. Efficiency of each machine against load current for constant speed and voltage operation.

26

SEPARATION OF LOSSES IN A DIRECT-CURRENT GENERATOR OR MOTOR

The losses in a generator or motor consist of copper losses, iron losses and mechanical losses.

The copper losses are the armature and field I^2R losses which may be readily determined for any given load and field condition.

The iron losses are due to pulsations and reversals of flux in the iron. The armature flux reverses its direction relative to the armature every time the armature moves a distance equal to the pole pitch. The movement of the armature teeth under the field poles causes pulsations in the pole-face flux density due to the difference between slot and tooth reluctance. Local variations in flux density are caused by the short-circuit currents in the coils undergoing commutation. Any non-magnetic pieces of metal or conductors located in a flux of varying density have eddy currents induced in them and, therefore, losses due to eddy currents: The iron loss is therefore made up of two components, namely—hysteresis and eddy-current losses.

The hysteresis loss is due to the characteristic of the iron by which it retains a portion of its magnetism unless forced to give it up by a reversed magnetomotive force. The evidence of this characteristic is shown by any complete magnetization loop in which the current or ampere-turns for a given increasing flux is greater than that for the same value of flux when decreasing. This effect is frequently attributed to internal friction between molecules. The net energy input to the iron to carry the flux through one complete cycle is proportional to the area of the so-called hysteresis loop. It has been found by experiment that the area of this loop for commercial iron is very closely proportional to the 1.6 power of the maximum flux density. The total power loss is, therefore, proportional to the volume of iron, the number of double reversals per second, and the 1.6 power of the maximum flux density,

$$P_h = K_h n \mathcal{B}_m^{1.6},$$

where K_h = hysteresis constant;
n = speed or frequency of reversal;
$\mathfrak{B}_m$ = maximum flux density.

No reduction in hysteresis loss results from laminating the iron.

The eddy-current loss is due to local currents induced in the iron by a varying flux. If flux in a conductor varies in density or direction, an electromotive force is set up which in turn causes a current to flow in such a direction as to oppose the change in flux density. This is commonly known as Lenz's Law. The strength of these currents is inversely proportional to the resistance of the material and their path is such that they encircle the flux producing them. The function of the laminations is to increase the resistance of the eddy-current path and consequently decrease the heating loss. The laminations are insulated from one another by insulating varnish or an oxide of iron so each eddy-current path is confined to one lamination. For a given width of lamination, since the thickness is negligible compared to the width, the length of any eddy-current path is independent of its distance from the center of the lamination. The flux linking any path is proportional to the distance, x, of the path from the center of the lamination. The cross-section of a differential path of unit width is dx. The voltage causing the current to flow is proportional to the area or x, whence $p_e = \frac{V^2}{\frac{\rho}{A}} = \frac{k^2x^2}{\rho}\,dx$ watts loss per path,

and $$P_e = \frac{2k^2}{T\rho}\int_0^{\frac{T}{2}} x^2 dx \text{ watts per unit volume,}$$

where k = constant;
x = distance from center of lamination to path under consideration;
ρ = the specific resistance of iron;
kx = voltage of elementary eddy current path;
T = thickness of lamination.

The above expression when integrated and limits substituted is as follows:

$$P_e = \frac{k^2}{12} \cdot \frac{T^2}{\rho},$$

which shows that the eddy current loss per unit volume is proportional to the thickness of the lamination squared and inversely proportional to the specific resistance of the iron. Since the voltage of any eddy-current path is proportional to the frequency or speed and maximum value of flux the above expression may be written as follows:

$$P_e = K_e T^2 n^2 \mathfrak{B}_m^2,$$

or for a given thickness of lamination

$$P_e = K_e n^2 \mathfrak{B}_m^2,$$

where K_e = eddy current constant;
n = speed or frequency of reversal;
$\mathfrak{B}_m$ = maximum flux density.

The expression for total iron loss is therefore as follows:

$$P_{h+e} = K_h n \mathfrak{B}_m^{1.6} + K_e n^2 \mathfrak{B}_m^2.$$

The mechanical losses consist of friction and windage losses; the friction loss being due to the bearings and brushes. The friction losses are proportional to speed and the friction coefficient. The windage losses for very low speeds are nearly proportional to the first power but as the speed increases this exponent increases and approaches the cube for very high speeds.

The I^2R losses in the field and in the armature winding can be very accurately determined for given currents; the only errors involved being those due to the presence of undetermined short-circuit currents in the armature coils undergoing commutation and due to variation of resistance with temperature. The second error can be eliminated by making measurements of resistance under proper temperature conditions. The I^2R loss in armature leads, brushes and brush-contacts cannot be so accurately determined on account of the variations with load. (For more detailed explanation see experiment 12.)

The iron losses may be determined accurately at no load for any speed and any net flux, but the iron loss is a function of flux distribution and since flux distribution is a function of armature current it is impossible to simulate full-load flux conditions at no load. The iron loss cannot be accurately determined under load conditions, consequently, it is customary to assume that the iron loss for a given net flux is the same at no load as at full load. This

is obviously not true but experience has proved that the difference is not great and consequently the assumption is justified.

The friction and windage loss is a complex function of speed and in case of a belt connection is also a function of load. It can be accurately determined at no load but not under load so it is customary to assume this loss independent of the load.

Method of apportioning Iron Loss between Hysteresis and Eddy-Current Losses.

Having determined the total iron loss under two or more conditions, it may be split up into the hysteresis- and eddy-current components by means of the theoretical relation derived above, namely:

$$P_{h+e}=K_h n \mathfrak{B}_m^{1.6}+K_e n^2 \mathfrak{B}_m^2,$$

for by knowing the total loss for two conditions, two simultaneous equations having the unknowns K_h and K_e may be set up and

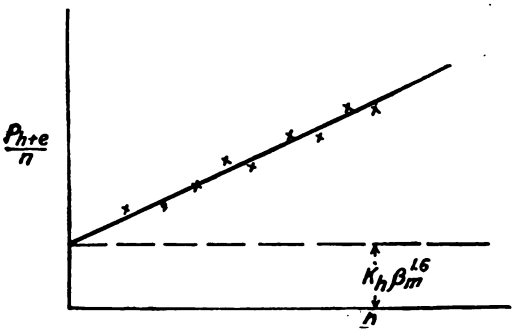


FIG. 58.

K_h and K_e determined from which the loss components may be derived. If a series of readings are taken for constant flux and varying speed, K_h and K_e may be determined graphically.

Divide total iron loss by speed, then

$$\frac{P_{h+e}}{n}=K_h \mathfrak{B}_m^{1.6}+K_e n \mathfrak{B}_m^2,$$

which for a constant $\mathfrak{B}_m$ makes $\frac{P_{h+e}}{n}$ a linear function of speed. If then $\frac{P_{h+e}}{n}$ is plotted against speed a fairly straight line should be obtained as in Fig. 58.

$K_h \mathfrak{B}_m^{1.6}$ is the intercept on the $\frac{P_{h+e}}{n}$ axis. The hysteresis loss at any speed is then

$$P_h = n(K_h \mathfrak{B}_m^{1.6}),$$

and the eddy current loss is

$$P_e = P_{h+e} - P_h.$$

Procedure.—The iron losses and mechanical losses are to be determined while the machine is running without load. This is done by driving the machine with a small motor, the input to which is measured and the output, which is the input to the machine under test, is determined by subtracting the losses of the driving motor from its input. In case a belt connection is used instead of a direct-connection the belt loss must also be subtracted. The belt loss may be determined approximately by measuring the difference in loss resulting by replacing the leather belt with a very light cotton belt for which the loss may be assumed zero. This must be done at light load in order that the cotton belt may be able to carry the load. The direct connection should be used if possible since the belt loss is not constant nor is it accurately attainable. The driving motor should be about $\frac{1}{15}$ the size of the machine under test since it supplies only the iron and mechanical losses. By having the small machine fully loaded its losses will be a small percentage of its output and consequently any error in determining its losses will not greatly affect the accuracy of the output determination.

Since the stray-power losses of the driving motor must be determined for many conditions of load and speed the labor will be materially reduced by keeping the field current constant and obtaining speed variation by varying the armature voltage. (For further discussion see experiment 23.)

The diagram of connections is given in Fig. 59. In all varying speed tests, vary the speed from 10 per cent. to 110 per cent. of rating. First determine the bearing friction and windage losses by running the machine with the field demagnetized and with the brushes lifted. Next lower the brushes and determine the total friction and windage losses. Finally excite the machine with

normal full-load flux and thus determine friction, windage and iron losses.

Make a stray-power run on the driving motor covering all conditions of flux and speed attained in the above tests.

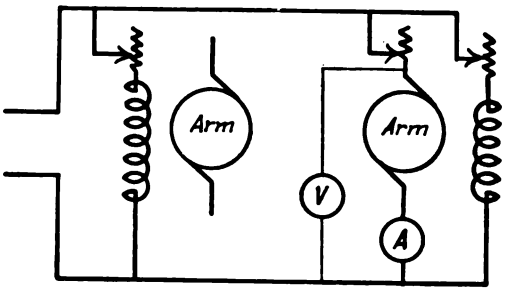


FIG. 59.

From the above data and armature and series field resistance measurements all losses can be determined.

Results Required.—

(*a*) The following curves from 10 per cent. to 110 per cent. rated speed:

1. Brush friction and speed.
2. Friction and windage against speed.
3. Core losses at full-load flux and speed.
4. Eddy current losses and speed.
5. Hysteresis losses and speed.
6. Belt loss and speed (if belt is used.)
7. Summation of 1, 2 and 3 against speed.

(*b*) Calculate full-load efficiency.

In calculating the field current at full load for the efficiency calculation assume the demagnetizing turns on the armature equal to 5 per cent. of the impressed field. The ratio of shunt to series turns, if machine is compound wound, should be supplied.

(*c*) Explain in detail, (1) How the eddy current and hysteresis losses may be separated by plotting core loss at constant flux divided by speed, $\frac{P_c}{n}$, against speed as abscissae? (2) How to determine the output of the driving motor at the different speeds?

(3) How to determine the value of field current which will produce full-load flux under test conditions? (4) State what errors are introduced in this method of determining efficiency.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. I, pp. 201, 306.

LANGSDORF, "Principles of Direct-Current Machines," 2nd Ed., p. 375.

B. G. LAMME, "Iron Losses in Direct-Current Machines," *Trans. A.I.E.E.*, 1916, p. 261.

C. J. FLECHHEIMER, "A Method for Separating No-Load Losses in Electrical Machinery," *Trans. A.I.E.E.*, 1920, p. 291.

27

HEAT RUN ON D-C. DYNAMO

The maximum continuous output of any piece of electrical apparatus is determined very largely by its heating under load. Consequently a heat run under rated conditions is an extremely important part of any acceptance test. A motor or generator may be perfectly satisfactory in so far as efficiency, regulation, etc., are concerned, but may be absolutely incapable of standing continuous service at the load for which it is designed on account of the excessive temperatures reached in its parts. If the temperature of a motor or other piece of electrical apparatus becomes excessive, its insulation will very rapidly deteriorate and finally break down.

In the Standardization Rules of the American Institute of Electrical Engineers, 1922, the following values for the maximum temperature and temperature rise under rated conditions of load are recommended:

The rise in temperature should be measured, except in the cases noted below, after a run of sufficient duration to insure practically constant temperature having been reached.

The Standardization Rules give three methods for temperature measurement.

1. The Thermometer Method in which the maximum permissible observable temperature is 15° C. less than value given in the following table.

2. The Resistance Method in which the maximum permissible observable temperature is 10° C. less than the value given in the following table.

3. The Imbedded Temperature-detector Method in which the maximum permissible observable temperature varies from 5° C. less than the value given in the table to a larger value less which depends on the voltage rating of the machine.

PERMISSIBLE TEMPERATURES AND TEMPERATURE RISES FOR INSULATING MATERIALS

Class	Description of Material	Maximum Temperature to which the Material May be Subjected	Maximum Temperature Rise
O	Cotton, silk, paper and similar materials, when neither impregnated nor immersed in oil	90° C.	50° C.
A	Cotton, silk, paper and similar materials, when so treated or impregnated as to increase the thermal limit, or when permanently immersed in oil; also enameled wire.	105° C.	65° C.
B	Mica, asbestos and other materials capable of resisting high temperatures, in which any Class A material or binder is used for structural purposes only, and may be destroyed without impairing * the insulating or mechanical qualities of the insulation.	125° C.	85° C.
C	Materials capable of resisting higher temperatures than Class B, such as pure mica, porcelain, quartz, etc.	No limit yet specified.	

* The word impair is here used in the sense of causing any change which would disqualify the insulation for continuous service.

Certain classes of motors, notably railway motors and series motors designed for intermittent service, are rated on a full-load duty for some specified time as an hour or half hour. The increase in temperature of the different parts of motors of this type at the end of a full-load run for the specified time should not exceed the values already given.

It is impossible to make a satisfactory full-load heat run in a laboratory period of two or three hours, unless either a very small machine or one designed for intermittent service be used.

Procedure.—The machine used for this experiment will be either a shunt or series motor. The machine will be loaded

by means of a brake or by driving another machine which can be loaded as a generator.

The proper connections for a heat run on a shunt motor and on a series motor are given in Figs. 60 and 61 respectively. *Rh* is a rheostat for keeping the voltage at its rated value.

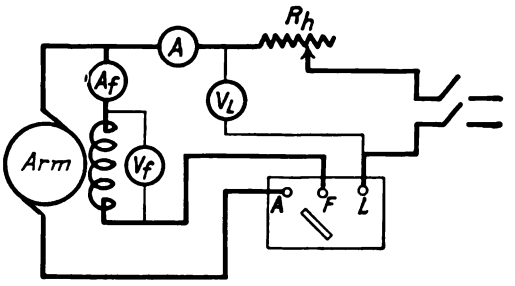


FIG. 60.

If a generator is to be used for load, it must be capable of absorbing without overload the power output of the motor under test. The proper connections for the generator are shown in Fig. 36.

Measure the resistance of the armature circuit, taking readings quickly to avoid any appreciable heating. The armature resistance

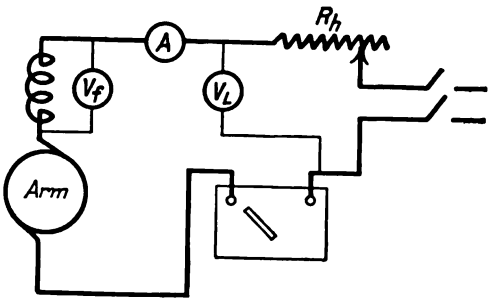


FIG. 61.

must be measured with the armature in a definite position which must be marked and used for the hot resistance measurement at the end of the test. *This resistance must not include the brush resistance.* See pages 17 and 85. Also record the temperature of the room near the machine and the temperature of the machine by thermometer.

Record the time at which the motor is started and *immediately* after starting take readings of the field current and field voltage

in order to get the *cold* resistance of the field. Apply the load—in case a series motor is used some load must be applied in starting—and adjust the rheostat *Rh* until rated voltage is impressed on the motor. If the line voltage is equal to the rated voltage of the motor, no rheostat should be used. Continue adjustments until the motor takes its rated current at its rated terminal voltage as indicated by V_L. Make these adjustments of current and voltage as quickly as possible and then record the speed of the motor.

Hold the voltage and current constant at rated values during the entire heat run, taking readings of speed, room temperature and all instruments at regular intervals. If it is possible to place thermometers on the field coils where they will not be broken, the readings of these thermometers should also be recorded.

The interval between readings should be short, from three to five minutes at the beginning of the run, but may be increased somewhat after the first half hour.

If a motor with continuous rating is tested, the heat run should be continued until the motor reaches constant temperature. If time will not permit of this, the run should be continued as long as possible, at least for an hour and a half. If the machine tested has a half-hour rating, the heat run should be continued only for this length of time.

At the completion of the heat run take final readings of all instruments, stop the motor and measure the resistance of its armature as quickly as possible.

NOTE.—Be sure that the hot and cold armature resistance measurements are made with the armature in exactly the same position.

As soon as the machine has been shut down, place a thermometer on its commutator and others on its field and bearings. These thermometers should be properly protected from radiation. See page 18.

Results Required.—

a. From the value of the field resistance obtained during the run, calculate and plot a curve of the temperature rise in the field against time. See page 16.

b. Calculate the final temperature and temperature rise in the armature.

c. Plot a curve showing the change of speed due to heating as a function of time.

d. The final temperature and rise in temperature in the bearings and commutator as determined by thermometer.

e. Does this machine fulfill the A. I. E. E. requirements as to temperature rise?

f. Determine the temperature rise for continuous operation by extending curve (*a*).

g. Can the rating of this machine be increased?

h. Does armature heating tend to increase or decrease the speed?

i. How does field heating affect the speed?

j. Determine for what period this machine can carry 25 per cent. overload.

k. A certain d-c. series motor is rated on the half-hour basis. Can it be operated on a load requiring 150 per cent. of full-load torque, if this load is on for five minutes and then the motor is stopped for five minutes, for three-quarters of an hour at a time. Plot temperature rise curve of the field from resistance measurements. If the final temperature does not reach that recommended by the A. I. E. E. determine from formula what time will be required for the temperature to reach this value.

l. Report on the desirability, from the temperature rise standpoint, of using a shunt motor in a commercial plant where it will be running at $\frac{3}{4}$ load and at $1\frac{1}{4}$ load, the load changing every fifteen minutes. Determine the stray power from no-load runs and calculate the efficiency at $\frac{3}{4}$ and $1\frac{1}{4}$ load. Determine the temperature rise by resistance measurements and thermometers.

LANGSDORF, "Principles of Direct-Current Machines," 2nd Ed., p. 390.

DAWES, "Electrical Engineering," vol. I, p. 368.

A great deal of information on temperature rise is given in *Trans. A.I.E.E.*, 1913, part I.

H. M. HOBART, "Electrical Machine Tests and Specifications Based on Modern Standards," *Trans. A.I.E.E.*, 1916, p. 1259.

B. G. LAMME, "Temperature Distribution in Electrical Machinery," *Trans. A.I.E.E.*, 1916, p. 1471.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. II, p. 74.

28

BALANCER SET

A balancer set is used to maintain approximate equality between the voltages on the two sides of a direct-current three-wire system. It consists of two identical rigidly coupled generators, usually compounded and connected with the armatures in series across the outside wires and the junction point connected to the neutral wire. When there is no current in the neutral both machines act as motors and draw only enough current to supply

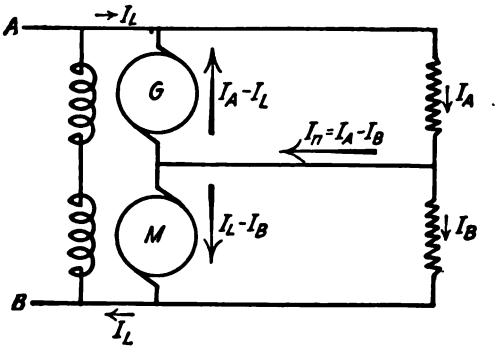


FIG. 62.

their losses. If side *A* of the line becomes more heavily loaded than side *B*, a current flows in the neutral wire. This current divides between the two armatures and the direction is such that the machine on the more heavily loaded side *A* acts as a generator and the machine on the less heavily loaded side *B* acts as a motor. See Fig. 62.

If neither machine had any armature reaction nor armature resistance the shunt fields could be connected in series across the outside wires and perfect balance would result, since the induced

voltages would be equal in magnitude to each other and with zero armature resistance their sum would equal the line voltage.

Since armature reaction and armature resistance cannot be eliminated it is necessary to counteract their detrimental effect by some means. This may be partially accomplished in several ways, i.e.:

a. By connecting the field of *A* from line *B* to neutral and the field of *B* from line *A* to neutral. This is called " Crossed Field Connection." In this arrangement the motor field is connected across the low-voltage side and the generator field across the high-voltage side. The generator voltage is thus raised both due to greater excitation and greater speed. This arrangement does not require compound fields but it does not give as good results as compound machines.

b. By connecting the shunt fields in series and across the mains and the series fields in series with their respective armatures. In this arrangement the series fields must be so connected that the motor is differentially compounded and the generator cumulatively compounded. This method gives very good results if the strength of the series field is properly adjusted.

c. By connecting the shunt fields in series across the mains and the series fields in series with the neutral. Again the series fields must be connected so that the motor is differentially connected and the generator cumulatively connected.

There is no marked difference between the characteristics obtained with connections (*b*) and (*c*). Both give very good results if the series fields are properly adjusted. It should be noted that in connection (*c*) the series fields carry twice the current as in (*b*) consequently for a given number of series field turns the characteristics will not be the same for the two connections. If the turns are correct for the (*b*) connection the voltage on the loaded side will rise with the (*c*) connection. Connections (*b*) and (*c*) are more satisfactory than (*a*) because voltage compensation depends upon neutral current and not upon an actual unbalance in voltage.

Procedure.—(Series fields disconnected.) *a.* Connect up the machines as indicated in Fig. 63 and vary the load from 0 to $2I$ where I is the rating of the machine. This large value of current can be carried safely since for this connection the current in each machine is approximately half of the load current. Actually the

motor current will be from zero to 25 per cent. greater than the generator current since the motor must supply all the losses. Take readings of line voltage, voltage to neutral, load current and speed.

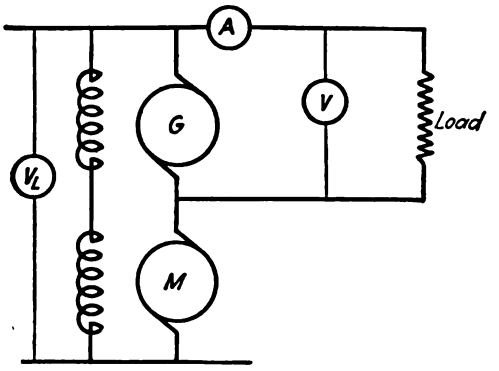


FIG. 63.

b. (Series fields disconnected.) Cross the shunt fields and repeat, taking care to adjust the shunt field resistances at the beginning of the run so that the voltage to neutral is exactly one-half of the line voltage.

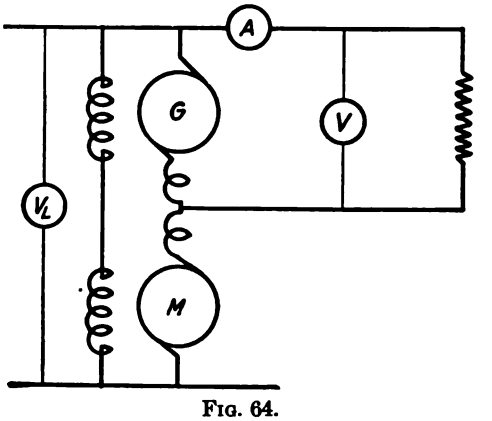


FIG. 64.

c. Connect the shunt fields in series across the mains and the series fields in series with their respective armatures as in Fig. 64.

To test for proper series field connections put full load on set and then short circuit the series field of the motor. If the speed decreases the motor field is properly connected. If the speed

increases, the motor series field should be reversed. Next short-circuit the series field of the generator. If the generator voltage decreases the connection is correct, if it increases the generator series field should be reversed.

Now vary the load and take readings as in (*a*).

d. Repeat (*c*) but with the series fields in the neutral wire. Carry unbalance current only to rated current of machine in this case. Make the same tests for series field connection as in (*c*).

Results Required.—

Curve of voltage of each machine plotted against current in the neutral wire.

a. With shunt fields in series across the line and series fields disconnected.

b. Same as in (*a*) but with the shunt fields connected to the neutral wire and crossed.

c. With shunt fields in series across the line and the series fields connected in series with their respective armatures.

d. With shunt fields in series across the line and the series fields connected in series with the neutral wire.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. I, p. 271.

LANGSDORF, "Principles of Direct-Current Machines," 2nd Ed., p. 416.

DAWES, "Electrical Engineering," vol. I, p. 391.

29

DYNAMOTOR

A dynamotor consists of a shunt machine with two commutators each connected to an independent armature winding. One of the armature windings and the shunt field are used as a shunt motor. The other armature winding acts as a generator.

Dynamotors are used to transform direct current from one voltage to another, in cases where the ability to regulate the voltage is unimportant. They are more efficient than motor-generators, since they require only one field and one armature, but have the distinct disadvantage of a fixed voltage ratio. Nothing which is done to either speed or field will alter this ratio, since both motor and generator windings are on the same armature and rotate in the same field.

The ratio between the armature voltages will depend solely upon the ratio of the number of turns in the two armature windings, while the ratio between the impressed and terminal voltages at any load will depend upon the ratio of the armature voltages and upon the resistance drops in the motor and generator windings.

If V_g and V_m represent respectively the terminal voltage of the generator winding, and the impressed voltage on the motor, and the subscripts g and m refer to the generator and motor, respectively,

$$V_g = (V_m - I_{a_m} R_{a_m}) \frac{N_g}{N_m} - I_{a_g} R_{a_g}, \quad . \quad . \quad . \quad . \quad (1)$$

where N_g and N_m are the numbers of turns in the two windings.

If there were neither armature copper nor stray-power losses the input to the motor armature would be equal to the output of the generator armature and the ampere turns of the two armatures would be equal and opposite. Under this condition the armature reaction would be zero. Since the losses in a good dynamotor are small, this condition is nearly realized.

Therefore no movement of the brushes with change in load is required. The brushes need only be displaced far enough from the neutral point for commutation.

Procedure.—Connect the motor side of the dynamotor as a shunt motor with a starting box. The generator winding should be connected to a bank of lamps, or other suitable resistance load. An ammeter and a voltmeter should be placed in each circuit. The proper connections are shown in Fig. 65.

When the dynamotor has been connected properly, start it as a shunt motor. Take readings of the speed and of all the instruments. Ammeter A_g should read zero. Apply load to the generator winding and take readings of speed, current and voltage

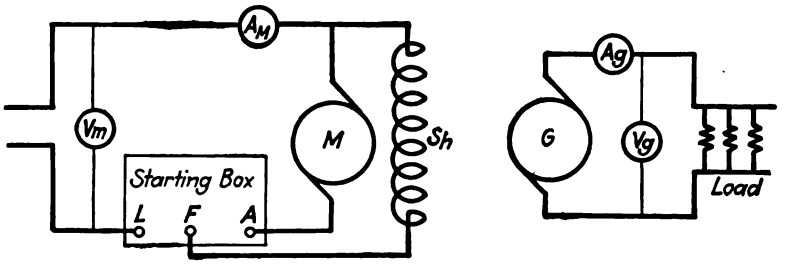


FIG. 65.

on both the generator and the motor sides for about eight to ten loads from no load to 25 per cent. overload.

When this has been done, stop the dynamotor and measure the resistances of the two armature circuits and the shunt field by the drop-of-potential method.

Overall efficiency $= V_g I_g \div V_m I_m$.
In equation (1)

$$\frac{N_g}{N_m} = \frac{V_g'}{V_m' - I_{a_m}' R_{a_m}}, \quad \ldots\ldots \quad (2)$$

where V_g' and V_m' are the no-load voltages of the generator and motor respectively, and I_{a_m}' is the no-load armature current of the motor side. This no-load armature current may be found by subtracting the current in the shunt field from the no-load motor current. The current in the shunt field may be measured, or it may be obtained by dividing the impressed voltage by the shunt field resistance.

In equation (1) I_{a_m} may be taken as approximately equal to

$$I_{a_g}\frac{N_g}{N_m}+I_{a_m}'. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

This assumes that the part of the motor current, I_{a_m}' which is used in supplying the no-load losses, remains constant and independent of the load.

Results Required.—

a. Efficiency against generator current.

b. Voltage against generator current.

c. Speed against generator current.

d. Resistance of each armature.

e. Calculated generator voltage against generator current.

f. How is the operation of the machine influenced by a change in field strength?

g. Should the brushes of a dynamotor be set ahead or behind the geometrical neutral? Why?

h. Will a series field on the output side improve voltage regulation?

i. What saving would result in the course of a year by using the dynamotor to cut down the voltage instead of a series resistance, if

1. The machine is operated at full load from rated voltage mains 44 hours per week.
2. Energy costs 2 cents per kilowatt hour.
3. Replacement cost of machine is (75+50×kw. capacity) dollars.
4. Life of machine is 20 years.
5. Interest on investment is 6 per cent.
6. Maintenance of machine is 1 per cent.
7. Cost of resistance element is $30.
8. Life of resistance element is 10 years.
9. Maintenance of resistance unit negligible.

j. How will the operation of the machine be affected if the brushes on either side should be out of position? How increase the terminal voltage of a dynamotor for a given impressed voltage?

k. If a 230-volt, 3-wire system is the source of power what

would be the saving in charging a storage battery from a dynamotor of 230–75 volts rating instead of from the line, if the battery has ten cells and the charging rate is 5 amperes at 28 volts for a period of 10 hours? The cost of power may be taken as 10 cents per kilowatt hour.

LANGSDORF, "Principles of Direct-Current Machines," 2nd Ed., p. 92.

30

THE DETERMINATION OF THE CANDLE-POWER OF AN INCANDESCENT LAMP

Primary Standards.—There is no satisfactory primary standard of light. All practical standards are flame standards and are therefore subject to variation in intensity with change in atmospheric pressure, humidity, etc. None are capable of being reproduced with satisfactory accuracy. It is doubtful whether any single flame standard can be reproduced closer than 1 or 2 per cent. with certainty.

The old standard in England and the United States was the English Standard Candle. It was a spermaceti candle about seven-eighths of an inch in diameter burning 120 grains an hour. At the best it was unsatisfactory and is discredited for all important work. The two best primary standards are the Pentane lamp (English), burning a gas obtained by passing air over pentane, and the Hefner lamp (German), burning amyl acetate. The Pentane lamp has an enclosed flame and is much less influenced by air currents than the Hefner lamp, which burns with an open flame. The flame of the Hefner lamp is of low intensity, 0.9 of a candle-power, and is of distinctly reddish color. The Pentane lamp is distinctly better in respect to both color and intensity. Its intensity is 10 candle-power and its color, although yellow, is much whiter than that of the Hefner lamp. It is a much more complicated lamp and it is doubtful whether it can be reproduced with nearly as great an accuracy as the much simpler Hefner lamp. Both are subject to about the same corrections for atmospheric conditions. Both lamps are far from satisfactory and can be considered only as laboratory standards.

The present standard of luminous intensity is the International Candle. It is derived from the mean intensity of a group of electric incandescent lamps maintained by the United States

Bureau of Standards at Washington in cooperation with similar groups of lamps maintained in France and in Great Britain. The Hefner is 0.9 of an international candle. The Pentane is 10 international candles. All measurements of candle-power and illumination are now expressed in terms of international candles.

Secondary Standards.—Well made properly seasoned incandescent lamps, preferably with tungsten filaments, are the most satisfactory secondary standards at present available. They are universally used for this purpose. Although incandescent lamps form excellent secondary standards, they cannot be reproduced with sufficient accuracy for primary standards. An incandescent lamp is entirely free from all atmospheric conditions and when

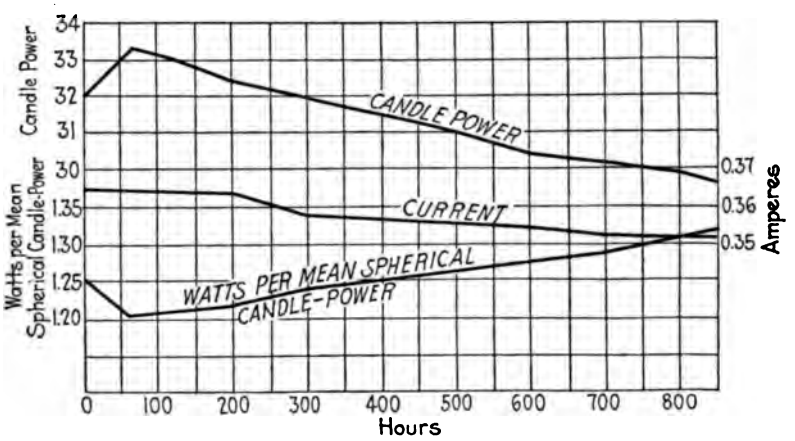


FIG. 66.—Characteristic curves of a 40-watt vacuum tungsten lamp.

properly seasoned and operated with care at either constant voltage or constant current may be used for a considerable number of hours without appreciable change in intensity. An incandescent lamp will not change in intensity except when in use.

Typical curves for a tungsten lamp of candle-power and watts per mean-spherical candle-power against hours burned are plotted in Fig. 66. The curves for a carbon-filament lamp are similar. Both carbon and tungsten-filament lamps show a rise in candle-power or intensity for the first 50 or 60 hours of their life. Their intensity then declines at a nearly uniform rate to the end of their useful life, which is from 600 to 1000 hours according to the type of lamp and the voltage at which it is operated. The decrease in

luminous intensity of a tungsten-filament lamp burning at normal voltage is about 10 per cent. in 800 hours. The rate of decline in the luminous intensity of a carbon-filament lamp in 600 hours is usually nearly 20 per cent. The rate of decline in intensity decreases rapidly as the operating voltage is decreased. It follows that a tungsten filament lamp may be operated for about 20 hours at normal voltage or a longer time at reduced voltage without a change in luminous intensity of more than $\frac{1}{4}$ of 1 per cent.

All incandescent lamps which are to be used as secondary standards should be carefully annealed by operating at a reduced voltage for 100 hours or more. The change in luminous intensity of an incandescent lamp with voltage is given approximately by

$$\frac{I_s'}{I_s} = k\left(\frac{V'}{V}\right)^n,$$

where I_s and I_s' are respectively the mean-spherical intensities at normal voltage, V, and at some other voltage, V'. The exponent n varies from about 6.9 for the untreated carbon-filament lamp to about 3.6 for the tungsten-filament lamp.

The approximate changes in luminous intensity for increases in voltage of 2 and 5 per cent. above normal are given for carbon- and tungsten-filament lamps in the following table:

Type of Lamp	Increase in Voltage above Normal	Increase in Candle-power above Normal
Carbon	2 per cent.	12 per cent.
Tungsten	2 per cent.	7 per cent.
Carbon	5 per cent.	32 per cent.
Tungsten	5 per cent.	19 per cent.

A slight increase in voltage produces a marked increase in the rate of decrease in luminous intensity with hours burnt and greatly shortens the life of a lamp. The effect is greater with a carbon-filament lamp than for one with a tungsten filament, principally on account of the difference in temperature coefficients of the filaments.

It is evident from the preceding table that the tungsten-filament lamp is more satisfactory than one with a carbon filament for a working standard. Either type of lamp must be operated at either

constant current or constant voltage. Constant-voltage operation is usually the more convenient although constant-current operation possesses certain advantages in some cases. The voltage or current must not be allowed to vary by more than $\frac{1}{10}$ of 1 per cent. for ordinary commercial work.

A properly seasoned and calibrated incandescent lamp may be set aside for use as a primary standard and used only for calibrating working standards. The Electrical Testing Laboratories in New York or the Bureau of Standards in Washington will calibrate suitable incandescent lamps for use as reference standards.

The intensity of an incandescent lamp varies with the direction in which it is measured. An incandescent lamp, when used as a standard, must therefore be calibrated and subsequently used either in a definite position or else rotating about its axis. In either case the intensity in a line perpendicular to the axis of the lamp through the center of its filament is used. The speed of the lamp if rotated must not be high enough to appreciably distort the filament but must be high enough to prevent flicker. If a lamp is carefully made and has the axis of its filament coincident with its axis of rotation a speed of 5 to 10 revolutions per second should be sufficient. Standard lamps are usually used stationary and must therefore be placed in exactly the position in which they were calibrated.

Mean-spherical Candle-power.—Since the luminous intensity of lamps varies with the direction in which it is measured, it is necessary to rate lamps in terms of their mean intensity, i.e., the average of the luminous intensities measured in all directions. The mean intensity is called the mean-spherical intensity or mean-spherical candle-power. The mean-spherical intensity may be obtained directly from one measurement by the use of special devices such as integrating spheres, or it may be obtained by rotating a lamp about its axis and measuring its candle-power or luminous intensity in different directions in a plane through the axis of its filament. When the latter method is used it is necessary to take into account the areas of the zones over which the candle-powers as measured are constant. This may be done graphically by what is known as the Rousseau[1] diagram or by weighting the zones. The latter method will be used in this experiment.

[1] KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. I, p. 208.

Determination of Mean-spherical Intensity.—If the lamp is assumed to be placed with the center of its filament coincident with the center of an enclosing sphere, the candle-power measured through any narrow zone on the sphere intercepted between two parallel planes, drawn perpendicular to the axis of rotation of the lamp, will be constant. Let Fig. 67 represent the lamp surrounded by a circumscribed sphere.

The dot-and-dash lines represent radii drawn in the plane through the axis of the lamp 15° apart. These radii intersect the surface of the sphere at the centers of 15° zones shown by the curved solid lines. The average luminous intensity through any zone such as the one at 45° will obviously be equal to that in the 45° direction provided the width of the zone is sufficiently narrow. The light emitted through any zone as the one at 45° is equal to the intensity or candle-power measured at 45° from the axis of the lamp multiplied by the area of the zone at 45°. If the area of each zone is multiplied by the candle-power measured at its center, the sum of the products of candle-powers by zonal areas divided by the area of the enclosing sphere will be the mean-spherical intensity or mean-spherical candle-power of the lamp. Factors which are proportional to the areas of 15° zones are given in the following table:

Angles	*Factors*
0 or 180 degrees	0.009
15 or 165 degrees	0.067
30 or 150 degrees	0.131
45 or 135 degrees	0.184
60 or 120 degrees	0.226
75 or 105 degrees	0.253
90 degrees	0.261

The factors are proportional to the areas of 15° zones extending $7\frac{1}{2}$° on both sides of the angles indicated. To use these factors find the product of the candle-power in each direction by the factor given in the table for the corresponding angle. The sum of these products divided by 2 is the mean-spherical intensity or mean-spherical candle-power of the lamp. The mean-horizontal intensity or candle-power is the mean candle-power measured in a plane perpendicular to the axis of the lamp at its center. If the lamp is rotating the mean-horizontal candle-power is the candle-power measured in a direction 90° from the axis of the lamp.

The ratio of the mean-spherical intensity to the mean-horizontal intensity is called the spherical reduction factor. This factor is constant for any given type of lamp and when known may be used to find the mean-spherical candle-power from the mean-horizontal candle-power.

Mean-spherical c-p. = Mean-horizontal c-p. × Spherical reduction factor.

$$I_s = I_h \cdot S.$$

If it is necessary to find the mean-spherical candle-power of a number of lamps of the same type, the mean-spherical and mean-

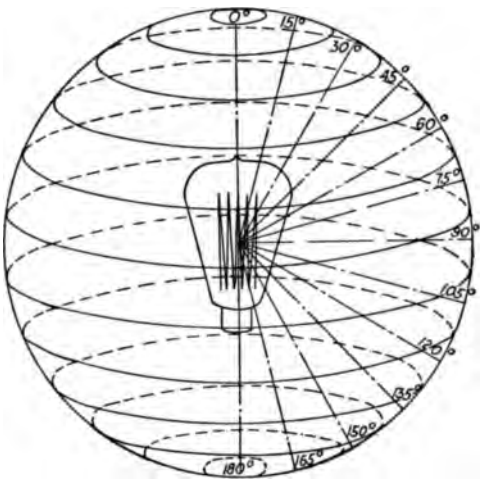


FIG. 67.

horizontal candle-powers of one only need be determined. From these the spherical reduction factor for the lamps may be obtained. The mean-spherical candle-powers of the other lamps will be equal to their mean-horizontal candle-powers multiplied by the spherical reduction factor.

The mean-spherical candle-power or intensity of a lamp is a measure of the total quantity of light given out by it. It is analogous to magnetic flux. The magnetic flux through any area is equal to the average magnetic intensity over the area multiplied by the area. Similarly, light flux through any area is equal to the average luminous intensity over the area multiplied by the area. If a source of light has an intensity of I_s candle-power in all direc-

tions, the intensity of illumination on an enclosing sphere of r meters radius is $\frac{I_s}{r^2}=E$ meter-candles or lux. Lux is the name given to unit of intensity of illumination, the meter-candle. The total quantity of light emitted by the source is equal to the intensity of illumination on the surface of the sphere multiplied by the area of the sphere or

$$\text{Flux}=\frac{I_s}{r^2}\times 4\pi r^2,$$

$$F=4\pi I \text{ lumens.}$$

The lumen is the unit of light flux. It is equal to the quantity of light emitted through a unit solid angle by a light source of one candle-power intensity. The light flux in lumens of a lamp is equal to its mean-spherical candle-power multiplied by 4π.

Vertical Distribution.—The vertical distribution shows the candle-power of a lamp in different directions about its center in a plane through its axis. It is a polar plot of the candle-powers measured in different directions in a plane through the axis of the lamp. Measurements for vertical distribution are usually made with the lamp rotating about its axis in order to get the mean of the vertical distributions in all vertical planes. The data required are the same as are needed for the determination of the mean-spherical candle-power. The mean-vertical distribution is necessary as well as the mean-spherical candle-power in order to determine the number and positions of lamps required to produce any desired illumination. When lamps are to be used with reflectors or shades, as is usually the case, the candle-power determinations should be made with the reflector or shade in place. It is also necessary to know the watts consumed by the lamps per lumen or per mean-spherical candle-power in order to determine the efficiency of any light installation.

Photometer.—A photometer is an instrument for measuring the relative intensities of two lamps or sources of lights. The eye cannot judge the relative intensity of two lights. It can, however, determine with considerable accuracy when two adjacent surfaces are equally illuminated.

All photometers are based on the production of equal illumination upon two surfaces placed so that each is illuminated by one of the two lights to be compared. The common way of varying

the illumination of the surfaces to produce equality is by moving the lights nearer or further away from the surfaces they illuminate. If the perpendicular distances between the illuminated surfaces and the lights being compared are measured, the relative intensity of the lights may be calculated.

The intensity of illumination of a surface, i.e., its brightness, is equal to the quantity of light it receives per unit area. It can easily be shown that this quantity varies inversely as the square of the distance of the surface from the light source.

For example: Suppose a, Fig. 68, is a luminous point. If F is the quantity of light given out by the point, F units of light must pass through any enclosing sphere. Let r be the radius of an enclosing sphere drawn about the point a as a center. The intensity of illumination on the surface of the sphere will be the quantity of light, F, emitted by the point divided by the area over which it is spread, that is, by the area of the sphere. Therefore, if E is this intensity of illumination

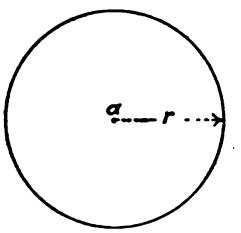


FIG. 68.

$$E = \frac{F}{\text{area of sphere}} = \frac{F}{4\pi r^2}.$$

If the radius of the sphere be increased, the intensity of illumination on its surface will vary inversely as the square of its radius or inversely as the square of the distance between the source and the surface.

The arrangement of an ordinary photometer is shown in Fig. 69. The two lights A and B to be compared are placed at opposite

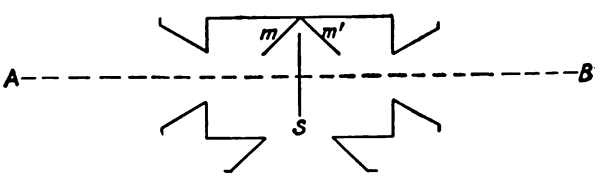


FIG. 69.

ends of a graduated bar. A small carriage mounted so that it can be moved along the bar is placed between the lights to be compared.

This carriage carries a screen S one side of which is illuminated by the light A. The other side is illuminated by the light B. By the use of two mirrors, m and m', or any other suitable device, both sides of the screen may be seen at once through the opening in the carriage.

The carriage is moved back and forth until both sides of the screen appear equally bright. Then, if I_{dA} and I_{dB} represent the intensities of the two lights and a and b their respective distances from the screen, the intensity of illumination, I_{dS}, on the screen will be

$$I_{dS}=\frac{I_{dA}}{a^2}=\frac{I_{dB}}{b^2}.$$

If the intensity of B is in candle-power, the candle-power of A will be

$$I_{dA}=I_{dB}\left(\frac{a}{b}\right)^2.$$

If the distance between the two lights is fixed and equal to x, and B is placed at the zero point of the bar

$$I_{dA}=I_{dB}\left(\frac{x-b}{b}\right)^2.$$

Photometer bars are usually from 100 to 200 inches long according to the size and intensity of the light sources to be compared. When a bar of fixed length is used it is convenient to have it graduated directly in ratios squared.

$$\left(\frac{x-b}{b}\right)^2=R.$$

Screens.—The Bunsen screen consists of a piece of thin white paper the center of which has been rendered translucent by means of paraffine. A medium weight smooth bond paper is quite satisfactory for a Bunsen screen.

If such a screen is illuminated from behind, more light will pass through the greased center than through the ungreased portion. The center will therefore appear brighter than the outside. If the screen is illuminated from the front, less light will be reflected from the center than from the ungreased outside. In this case the center will appear dark.

If such a screen is placed between two lights the greased center will appear dark on the side which receives the more light. If the screen is moved back and forth between the two lights the center will appear first dark on one side and then on the other. When the illumination on the two sides of the screen is the same, the two sides will appear alike, with the greased spot very slightly darker than the rest of the screen.

The Bunsen is now seldom used. It is usually replaced by the Lummer Brodhun optical screen which, in its simplest form, is equivalent to a perfect Bunsen screen. With the Lummer Brodhun screen the center spot which is produced optically disappears for a balance when the lights compared are the same color. The grease spot of the Bunsen screen can never be made to completely disappear. The contrast form of Lummer Brodhun Screen is usually used in preference to the simpler as it is much more sensitive. The principle of the simple and contrast screens is the same. A description of them will be found in any of the handbooks for electrical engineers and in books on photometry.

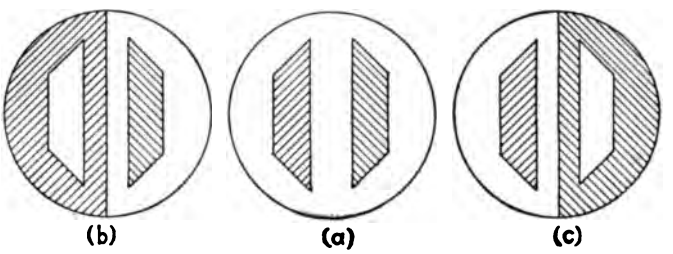


FIG. 70.

The field of the contrast screen, which is circular, is divided into two parts vertically. In the center of each of these two semicircular parts formed by the division is a trapezoid. These two trapezoids are slightly dimmed by smoked glass screens so that when a balance is obtained they are still slightly visible. With the smoked screens removed the whole field would appear equally illuminated for a perfect balance without any lines of demarcation provided the lights compared were the same color.

The appearance of a contrast screen for a balance and out of balance is shown in Fig. 70.

Fig. 70 (*a*) shows the appearance for balance. Figs. 70 (*b*) and (*c*) show the appearance after the screen has been displaced slightly

first on one side and then on the other side of the balanced position.

Rating of Incandescent Lamps.—Most incandescent lamps are now rated in watts at the voltage at which they should be used, except street series lamps which are rated in lumens and current. The candle-power rating when given should be the mean-spherical candle-power and the efficiency should be in watts consumed per mean-spherical candle-power or in lumens per watt. Lamps were formerly rated in terms of mean-horizontal candle-power, i.e., the average candle-power of a lamp in a plane through the center of the lamp perpendicular to its axis. Such ratings were unsatisfactory and had little significance except when applied to a particular type of lamp.

Types of Incandescent Lamps.—There are three types of incandescent lamps at present in use. These are: the carbon-filament lamp operating at an efficiency of about 4 watts per mean-spherical candle-power, with a useful life of about 600 hours for a decline in candle-power during life of 20 per cent.; the metalized carbon filament lamp (obsolete) operating at about 3 watts per mean-spherical candle-power, with a useful life of from 600 to 800 hours according to the efficiency selected for a decline of about 20 per cent. in candle-power during life; the vacuum tungsten-filament (Mazda *B*) lamp operating at an efficiency of about $1\frac{1}{4}$ watts per mean-spherical candle-power, with a useful life of about 1000 hours for a decline in candle-power of about 10 per cent. during life, and the gas-filled tungsten-filament lamp operating at from about 0.6 to 1.1 watt per mean-spherical candle-power according to the size, with a useful life of about 1000 hours for a decline in candle-power of not over 10 per cent. during life. The manufacture of the metalized carbon-filament lamp was discontinued in the summer of 1918 as a fuel conservation measure and the use of the carbon filament lamp was restricted to places where excessive vibration would not permit the use of the more fragile tungsten lamps. Its manufacture was not resumed because the carbon lamp was more rugged and the tungsten lamp was more efficient.

Electrical Connections.—The electrical connections used in this test are shown in Fig. 71.

R_x and R_s are resistances for coarse adjustment. The small letters, r_m, r_x and r_s, represent carbon compression-block rheostats for fine adjustments. The resistance, r_m, will affect the

voltage of both lamps. The other resistances affect principally the voltage of the lamp in whose circuit they are placed. An ammeter is placed in the circuit of the lamp to be tested. Suitable potential leads are brought to a voltmeter so that by the use of transfer switches the voltage of either lamp, the voltage of the mains or the voltage difference between the lamps may be read. The voltmeter must be connected to the lamp being tested while the current taken by this lamp is being read and, since the current taken by the voltmeter will in most cases be 1 or 2 per cent. of the current taken by the lamp, it must be corrected for.

Procedure.—First calibrate a seasoned lamp for a secondary standard by means of a reference standard lamp. The seasoned lamp should be placed in the non-rotating holder at the end of the photometer bar and the reference standard lamp at the

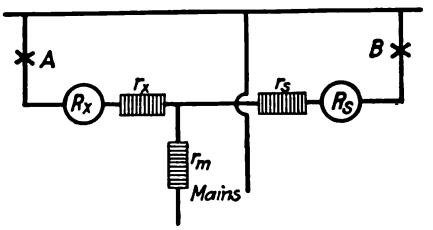


FIG. 71.

other end. The reference standard should be burned for only the briefest possible time at rated voltage, since its calibration will will change.

Leave the calibrated secondary incandescent standard lamp in the non-rotating holder at the end of the photometer bar. It should be with the center of its filament on a line drawn parallel to the photometer bar and passing through the center of the photometer screen. The lamp must be in the same position as when calibrated. The standard lamp should be placed with the axis of its filament directly over the zero point of the photometer bar. Place the lamp to be tested at the other end of the photometer bar at a definite distance from the standard lamp. Adjust the lamp to be tested so that the center of its filament is on the line through the center of the photometer screen. The socket for the lamp to be tested is arranged to be rotated about its axis by a small motor at from six to ten revolutions per

second. It may also be rotated by hand about a horizontal or vertical axis to any desired position, the positions being indicated in degrees on two graduated scales.

After the lamps have been properly placed, loosen the carbon rheostats and put all the resistance in the rheostats for coarse adjustment, then close the main switch on the switchboard. Connect the voltmeter to the standard lamp, then slowly bring its voltage up to the value at which it was calibrated by means of the rheostats R_s, r_s and r_m; be careful not to allow the voltage to go above the proper value. A very moderate increase over normal voltage will cause a rapid change in the calibration of the lamp and will necessitate recalibration. When the voltage of the standard lamp has been adjusted, bring the lamp to be tested up to voltage by means of the rheostats R_x and r_x. Readjust the voltage of the standard, then connect the voltmeter to read the difference in voltage between the lamps. This should be the difference between the rated voltages of the two lamps. If it is not, readjust the voltages.

If the difference in voltage is small, as will be the case when a standard has been selected of about the same voltage as the lamp to be tested, and is kept constant, any slight fluctuation in the voltage of the line will affect the voltages of both lamps by nearly the same percentage. If both lamps are of about the same efficiency any slight change in the voltage of the mains will affect the candle-power of both lamps by about the same amount and their relative candle-powers will remain unchanged. A storage battery should be used to supply power for this test. There should therefore be no fluctuation of the voltage of the mains.

Having adjusted the voltages of the lamps make several settings of the photometer. Connect the voltmeter to give the voltage of the lamp being tested. If this has changed readjust it by means of the carbon rheostat r_x. Connect the voltmeter again to read the voltage difference. If this has changed readjust it by the rheostat r_s. Read the ammeter and voltmeter simultaneously. Now measure candle-powers, voltage and current in different planes by 15° steps.

Results Required.—

a. Voltage, current and power of the tungsten (Mazda *B*) tested.

b. Polar plot of the vertical distribution plotted from readings of candle-power taken every 15° with the lamp rotating about its axis. Take the zero-degree point at the tip of the lamp. The 90-degree reading will then be the mean-horizontal candle-power.

c. Mean-spherical candle-power and intensity in lumens calculated from 15° zones.

d. Efficiency in watts per mean-spherical candle-power and in lumens per watt.

e. Spherical reduction factor.

f. Curve of efficiency in lumens per watt against voltage from 90 per cent. to 110 per cent. of voltage rating of lamp.

g. Lumens output against voltage from 90 per cent. to 110 per cent. of voltage rating of lamp.

h. Power taken, efficiency and candle-power at rated voltage from curves (*f*) and (*g*).

i. Repeat (*b*), (*e*), (*f*), and (*g*) for a carbon lamp.

j. Repeat (*b*), (*e*), (*f*), and (*g*) for a gem lamp.

k. Repeat (*b*), (*e*), (*f*), and (*g*) for a gas-filled Mazda *C*.

l. Repeat (*b*), (*e*), (*f*), and (*g*) using proper shade for lamp used.

m. Take an automobile headlight with 21 candle-power Mazda C lamp properly focused for the type of lens used and take distribution curves in vertical and horizontal planes and in one or two intermediate planes.

"Standard Handbook for Electrical Engineering," (14).

PENDER, "Handbook for Electrical Engineers," p. 1039.

KARAPETOFF, "Experimental Electrical Engineering," vol. I, p. 208; vol. II, p. 303.

DAWES, "Electrical Engineering," vol. II, chap. XIII.

31

SINGLE-PHASE A-C. CIRCUITS CONTAINING RESISTANCE, INDUCTANCE AND CAPACITANCE

a. Series Circuits.—In a direct-current series circuit, the current is the same in all parts and the algebraic sum of the voltage drops across the circuit is equal to the impressed voltage. The voltage drop across any one of the components must always be less than that across the entire circuit.

In the case of an alternating-current series circuit the conditions are somewhat similar. The current is the same in all parts of the circuit, and the *vector sum* of the voltage drops across the component parts of the circuit is equal to the total impressed voltage. If the circuit contains both capacitance and inductance, the voltage drop across the capacitance or the inductance may be greater than the voltage impressed on the circuit.

The current in a series circuit containing resistance, self-inductance and capacitance is given by the following expression:

$$I = \frac{V}{\sqrt{R^2 + (\omega L - 1/\omega C)^2}},$$

where L and C are, respectively, the self-inductance and capacitance, and ω is equal to $2\pi f$ where f is the frequency of the impressed voltage. R represents the total effective resistance of the entire circuit.

The reactance due to the self-inductance in the circuit is numerically equal to ωL and will be denoted by X_L, and that due to the capacitance is equal to $1/\omega C$ and will be denoted by X_C. Reactance multiplied by the current gives the voltage necessary to overcome the electromotive force of reactance just as the resistance of a circuit multiplied by current gives the electromotive force necessary to overcome the drop in potential due to resistance.

The current in a circuit containing nothing but resistance is in phase with the impressed voltage. If the circuit contains only self-inductance, the current will be 90° behind the impressed voltage while if it contains nothing but capacitance the current will be 90° ahead of the voltage. Since the effects of capacitance and self-inductance are opposite, in so far as lead and lag are concerned, the reactances due to them are written with opposite signs. Reactance due to self-inductance is considered positive; that due to capacitance negative. The equation given above may be written

$$V = I\sqrt{R^2 + (X_L - X_C)^2}.$$

The power consumed in any circuit is always given by $VI \cos \theta$, where V and I are respectively the impressed voltage and current. θ is the angle of lag or lead of the current, I, with

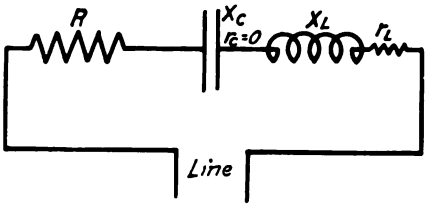


FIG. 72.

respect to the voltage, V. Since θ due to either pure capacitance or pure self-inductance is 90°, the power lost due to either is zero.

Condensers and reactance coils cannot be made without some resistance. This causes a loss due to I^2R. The presence of iron in reactance coils also causes more or less loss. The dielectric of a condenser may cause a loss due to dielectric hysteresis. On account of these losses, the phase difference between the currents and the voltages in condensers and reactance coils will not be quite 90°, but will be enough less to give a component of the voltage along the current to supply the losses.

The actual voltage drop across capacitances and inductances will be given by

$$I\sqrt{X_C^2 + R_C^2},$$

and

$$I\sqrt{X_L^2 + R_L^2},$$

where R_C and R_L are the effective resistances. The expressions $\sqrt{X_C^2+R_C^2}$ and $\sqrt{X_L^2+R_L^2}$ are called the impedances. The energy lost will be given by the current squared multiplied by the resistance. I is the current in the circuit and V is the impressed

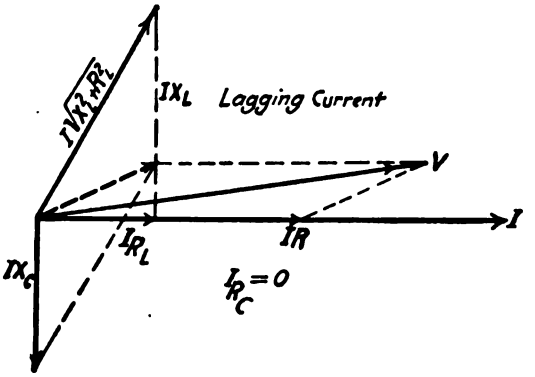


FIG. 73.

voltage. V is equal to the vector sum of the voltage across the resistance, IR, the voltage across the condenser, IX_C (R_C assumed to be zero), and the voltage across the reactance coil, $I\sqrt{X_L^2+R_L^2}$.

From Fig. 73 it can readily be seen that the voltage across either the condenser or the reactance may be greater than the

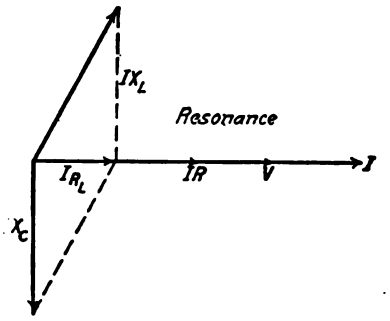


FIG. 74.

impressed voltage. When $IX_L=IX_C$ this diagram becomes Fig. 74, which is the condition for resonance.

When the wattless components of the voltages across the condenser and inductance are equal, the circuit is said to be in reso-

nance and the current follows Ohm's Law, $I = \frac{V}{R+R_C+R_L}$. The wattless components are the components perpendicular to the current.

b. Parallel Circuits.—In a direct-current circuit consisting of a number of parallel branches, the voltage impressed is the same

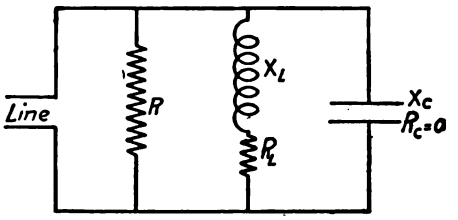


FIG. 75.

on all branches and the total current supplied to the circuit is equal to the sum of the currents in the different parts. In an alternating-current parallel circuit the same relation holds provided the sum of the component currents is taken vectorially.

If the parallel branches of an alternating-current circuit contain self-inductance and capacitance, the currents in these branches may be greater than the current supplied to the entire circuit from the mains.

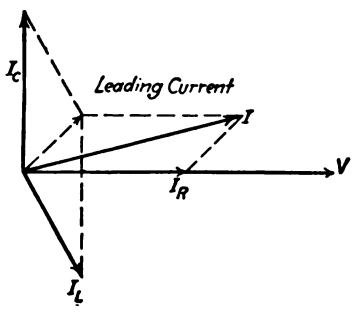


FIG. 76.

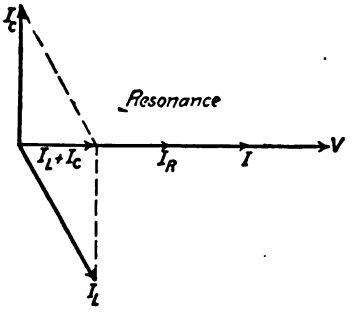


FIG. 77.

In Fig. 76 V is the impressed voltage and I the current supplied to the entire circuit. I is the vector sum of the current in the resistance, I_R, the current in the reactance coil, I_L, and the current in the condenser I_C.

When the wattless components of the currents taken by the

condenser and reactance coil are equal, the circuit is said to be in resonance.

It can easily be seen from Fig. 76 that the current in the capacitance or in the inductance branch may be greater than the current supplied to the entire circuit from the mains. When I_C equals the quadrature component of I_L this diagram becomes Fig. 77, which is the condition for resonance.

If any of the parallel branches should contain resistance, capacitance and self-inductance in series, the current in each branch could be found as indicated under series circuits. The vector sum of these currents would then be the total current supplied from the mains.

Procedure.—*a*. Before performing this experiment read what is given under Wattmeters (cf. pages 4 to 9).

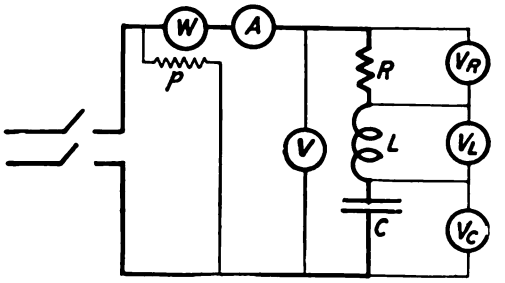


FIG. 78.

Make up a series circuit of constant resistance, variable capacitance and variable inductance. The proper connections are shown in Fig. 78.

When a section of condenser is disconnected, the small switch disconnecting it should be placed in the position marked out or discharge. If this precaution is not taken severe shocks may be received from what are apparently dead sections. The effective resistance of the condenser used in this test should be very small and may be assumed zero.

1. Place all the switches on the condenser boxes in the discharge position, set the inductance coils for maximum reactance (iron cores in), then close the main switch. No current should flow. Now close the switches on the condenser boxes one at a time and note the effect on the current. Continue closing the switches until the voltages about the condenser and inductance

coils are approximately equal. Since the resistance of the inductance coils is very small resonance will be approximately obtained when the voltage drops across the condenser and the inductance coils are equal. These drops may be made exactly alike by adjusting the inductance coils. The voltage across the condenser and that across the inductance coils may now be considerably greater than the voltage of the mains. Read all six instruments, simultaneously. Consider the resistances of V_R, V_L and V_C as part of their respective branches.

2. Reduce the inductance in the circuit considerably by raising the core of one of the inductance coils. Again read the instruments.

3. Open the main switch, cut out the inductance coils and take a set of readings.

4. Replace inductance and obtain a set of readings with the condenser taken out of circuit.

The power factor under the different conditions may be calculated by P_0/VI_0 where the symbols represent the corrected readings of the instruments in the main line (see page 8). If the instruments are connected as shown, the reading of the wattmeter should have subtracted from it the power, I^2r_w, consumed by its current coil, the power, I^2r_a, taken by the ammeter and the power, V^2/r_v, taken by the voltmeter, where r_w, r_a and r_v are the resistances of the wattmeter current coil, the ammeter and the voltmeter respectively. The ammeter reading must be corrected vectorially for the current taken by the voltmeter. (See page 8).

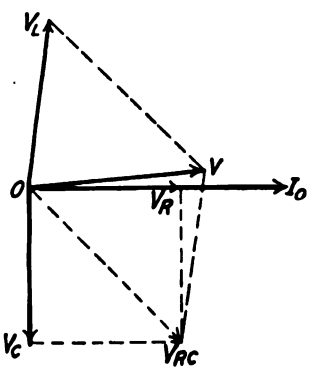


FIG. 79.

Vector diagrams for these four conditions can be constructed as follows:

Referring to Fig. 79 draw a horizontal line OI_0 to represent the current.

The voltage required to force the current through the resistance will be in phase with the current. Lay off a distance OV_R along the current line equal to this voltage as measured. A good scale to use is 40 volts to the inch.

The current in the condenser will lead the impressed voltage by 90°. In other words the voltage will lag 90° behind the current. Measure lag in a clockwise direction and lay off a distance OV_C equal to the condenser voltage, lagging 90° behind the current.

The vector sum of OV_R, OV_C and the voltage around the reactance coils must be equal to the impressed voltage V.

Find the resultant of OV_R and OV_C by completing the parallelogram $V_COV_RV_{RC}$. With O as a center and a radius equal to the voltage, V, impressed on the entire circuit, swing an arc. Also swing another arc with V_{RC} as a center and a radius equal to the voltage, V_L, across the reactance coils. A line joining O with the intersection of these two arcs will fix the direction of the impressed voltage V.

To complete the diagram draw a line OV_L upward from O equal and parallel to the dotted line $V_{RC}V$. This line, OV_L represents in phase and magnitude the voltage across the reactance coils.

The cosine of the angle I_0OV is the power factor of the entire circuit and should, if the instruments are correct and the diagram is carefully drawn, be equal to the power factor of the circuit as given by P_0/VI_0.

b. Make up a circuit with the resistance, inductance and capacitance in parallel, using the same resistance, inductance and capacitance as were used in part *a*. A short-circuit block should be placed in each branch so that an ammeter may be inserted. A wattmeter, an ammeter and a voltmeter are connected so as to measure the watts, current and voltage supplied to the entire circuit. If a sufficient number of ammeters are available, one can be put in each branch of the divided circuit, if not, one ammeter will have to be shifted from one branch to another.

The proper connections are shown in Fig. 80.

Place all the condenser switches in the position marked discharge and set the cores of the inductance coils for maximum reactance, then close the main switch.

1. Connect the condenser sections one by one until the ammeter in the condenser circuit reads approximately equal to the inductance current. Notice the decrease in the current indicated by the main line ammeter. When this has been done adjust the inductance coils until the current taken by them is exactly equal to the condenser current. Watch the main line ammeter as this

is done. Since the resistance of the inductance is small, the circuit will now be approximately in resonance. Read all instruments.

Since the currents taken by the condenser and reactance coils are equal and about 180° apart in phase, the current coming through the main line ammeter to supply these is very small. If there were no losses in either the condenser or the inductance coils and the currents taken by them were equal, the current supplied to them from the line would be zero.

2. Open the circuit of the resistance and again take readings of all instruments. Compare the line current with the current

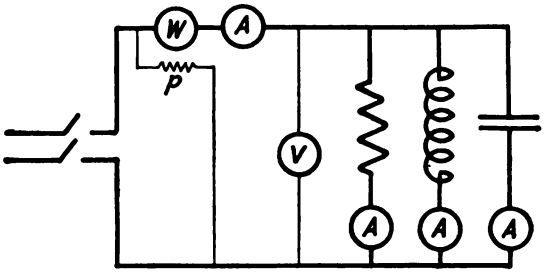


FIG. 80.

taken by the condenser and inductance coils. If possible use a low-range ammeter and low power-factor wattmeter here.

3. Put back the resistance and the instruments used in *b*.1, open the circuit of the condensers or the inductance coils and take readings. If the circuit of the inductance coils is opened the line current will lead the impressed voltage; if, however, the condenser circuit is opened the current will lag.

4. Put the condenser and inductance coils again in circuit and destroy the condition of resonance by raising the cores of the inductance coils. Record the readings of all instruments.

Vector diagrams for the above four cases may be drawn as follows:

Referring to Fig. 81 lay off a horizontal line equal to the impressed voltage V. The current in the resistance will be in phase with V. Lay off this current OI_R to scale along V. The condenser current, I_C, leads the voltage V by 90° and should be drawn vertically upward from OV. Find the vector sum of OI_C,

and OI_R by constructing the parallelogram $I_R O I_C I_{RC}$. Then the sum of OI_{RC} and the current, I_L, in the inductance must be equal to the current, I_0, supplied by the line. With I_{RC} as a center and with a radius equal to the current in the inductance coils swing an arc. Swing another arc with O as a center and with the line current I_0 as a radius. A line joining O and the intersection of these two arcs will represent the line current in phase and magnitude. To complete the diagram draw the current in the reactance coils OI_L downward from O parallel to the line $I_{RC}I_0$.

The cosine of the angle I_0OV is the power factor of the entire circuit and should, if the instruments are correct and the diagram

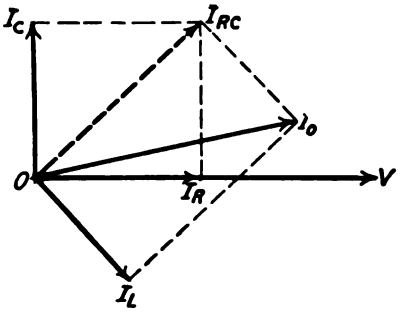


FIG. 81.

is carefully drawn, be equal to the power factor of the circuit as given by P_0/VI_0.

Results Required.—

a. Vector diagrams for the above four cases in series circuits.

b. Vector diagrams for the above four cases in parallel circuits.

c. Discuss any discrepancies between the values of power factor as obtained from the diagrams and from calculation.

d. By means of a low-power-factor wattmeter measure the phase angle of the condenser used and state what the effect on the results would be by assuming the condenser current to lead the voltage by 90°.

e. If the voltage impressed on the series circuit containing resistance, inductance and capacitance is a pure sine wave and the inductance coil is wound on an iron core will there be any third harmonic in the current? Draw a vector diagram representing

the third harmonic voltage condition. What is the source of the third harmonic voltage?

f. If the impressed voltage contains a seventh harmonic, in which circuit, series or parallel, will it produce the greatest seventh harmonic current?

g. Why would not a series circuit in resonance be just as satisfactory a source of high voltage as a step-up transformer?

h. When performing series circuits, measure the voltage across R and C in series. This will give the actual value of V_{RC}. Construct the exact diagram.

i. When performing parallel circuits, measure the vector sum of the currents I_R and I_C. Construct the exact diagram.

j. When adjustment has been made for resonance in series circuits vary frequency and take readings.

k. Repeat *j*, for parallel circuits.

LAWRENCE, "Principles of Alternating-Currents," chap. VII.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. II, p. 13.

DAWES, "Electrical Engineering," vol. II, p. 22.

JACKSON, "Alternating-Currents and Alternating-Current Machinery," p. 257.

V. BUSH, "Oscillating-Current Circuits by the Method of Generalized Angular Velocities," *Trans. A.I.E.E.*, 1917, p. 207.

B. G. LAMME, "The Technical Story of Frequencies," *Trans. A.I.E.E.*, 1918, p. 65.

HUDSON, "Engineering Electricity," chap. VI.

GRAY, "Principles and Practice of Electrical Engineering," 2nd Ed., chaps. XXIX and XXX.

32

EFFECTIVE RESISTANCE

The voltage induced by magnetic induction in any conducting loop is proportional to the rate of change of the number of lines of induction threading the loop. When the lines of induction are changing at the rate of one line per second, the induced voltage is 10^{-8} volts or one abvolt.

If lines of induction exist in conducting masses of metal, or any other material, and the density of the lines is not constant, voltages are induced which cause currents to circulate in the material, *the path of the current being a closed loop encircling the flux of induction and the direction of the current is such that the flux due to the current tends to oppose any change in the inducing flux.* In other words the induced currents oppose the action which produces them.

An inductance coil upon which an alternating voltage is impressed will, therefore, have eddy currents induced in the conducting turns, or if any other masses of metal are subjected to the action of the flux set up by the current in the coil, they also will have currents induced in them. Since these eddy currents set up a flux which opposes the change in the inducing flux, they produce a voltage in the turns of the coil, which is in the same direction as the current and thereby cause an increase in the coil current. This increase in the coil current supplies the I^2R losses caused by the eddy currents. The symbol used for the ohmic resistance of the circuit is R_{oh}. R_e represents the effective resistance of the circuit.

$$R_e = \frac{\text{Power}}{I^2},$$

$R_e - R_{oh}$ = increase in resistance due to the eddy currents.

The line *oa* of the vector diagram, Fig. 82, represents the voltage impressed at the terminals of an impedance coil, and *oe* is the

current flowing. The line *ob* is 90° ahead of the current and is the equivalent reactance drop, and *ba* is the effective resistance drop. *ca* is the drop due to the ohmic resistance of the winding. The voltage due to the true self-induction is the impressed voltage minus the ohmic resistance drop and is represented by *oc*. The line *od* is 90° behind *oc* and represents the magnetizing com-

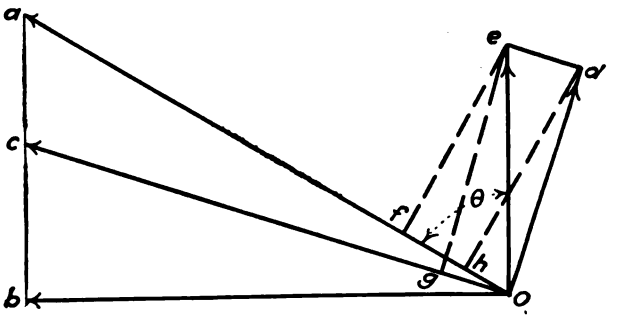


FIG. 82.

ponent of the current. The current *de* supplies the eddy-current loss.

$oh \times oa$ = ohmic resistance loss due to magnetizing current *od*.

$og \times oc$ = eddy current loss.

$hf \times oa$ = eddy current loss plus the ohmic resistance loss due to the component of current *de* which supplies eddy current losses.

$(oh+hf)oa = of \times oa$ = eddy current losses plus the total ohmic resistance loss.

$$= VI \cos \theta.$$

$$\text{True self-inductance} = \frac{oc}{od \times \omega}.$$

The above analysis assumes that all voltages and currents are pure sine waves. If the magnetic circuit of the inductance coil contains iron the current wave will contain harmonics even though a pure sine wave of voltage is impressed upon the coil. There will be hysteresis loss in the iron which will increase the effective resistance. The resulting conditions cannot be represented by means of a vector diagram, but a very close approximation may be obtained by using equivalent sine waves.

Calculation of Self-inductance of a Solenoid.—The self inductance of a solenoid of which the ratio of length to diameter is 50 or more, can best be determined by summing up the total linkages due to unit current. The total linkages* per ampere divided by 10^8 is then the self inductance in henries.

Consider a solenoid of total length l, n layers, and N turns per layer. Let d_1 be the diameter of the inner layer, d_2 that of the second, etc., then the linkages with the inner layer due to unit current in all the layers will be

$$\lambda_1 = \frac{.4\pi N}{l} \cdot N \cdot n \frac{\pi d_1^2}{4} = \frac{.4\pi^2 N^2}{4l} n d_1^2,$$

the linkages with the second layer,

$$\lambda_2 = \frac{.4\pi^2 N^2}{4l} [d_2^2(n-1) + d_1^2],$$

and those with the nth layer,

$$\lambda_n = \frac{.4\pi^2 N^2}{4l} [d_n^2\{n-(n-1)\} + d_{n-1}^2 + d_{n-2}^2 \ldots d_{n-(n-1)}^2].$$

Then adding to obtain total linkages,

$$\sum \lambda = \frac{.4\pi^2 N^2}{4l} [d_n^2 + 3d_{n-1}^2 + 5d_{n-2}^2 \ldots (2n-1)d_1^2].$$

and the self-inductance,

$$L = k\Sigma\lambda 10^{-8}$$

$$= \frac{k\pi^2 N^2 \times 10^{-9}}{l} [d_n^2 + 3d_{n-1}^2 + 5d_{n-2}^2 \ldots (2n-1)d_1^2],$$

where N = total turns per layer;
l = length of solenoid in centimeters;
d_n = mean diameter of the nth layer in centimeters.

The correction factor, k, to take care of the leakage through the end turns is given in the following table:

Ratio of Diameter to Length	k
0.00	1.000
0.05	0.979
0.10	0.959
0.15	0.939
0.20	0.920

A simple approximate formula for the inductance of a multiple layer solenoid is

$$L=\frac{\pi^2 n^2 N^2 d_1^2}{l+\frac{d_1+d_n}{4}}\cdot\frac{d_n}{d_1}10^{-9},$$

where the symbols have the same meaning as above.

More exact formulae may be found in the Circulars of the U. S. Bureau of Standards.

Apparatus.—A solenoid which is of such dimensions that its self-inductance may easily be calculated.

Procedure.—1. With no metal of any kind inside of the coil, measure the ohmic resistance of the inductance coil using direct current.

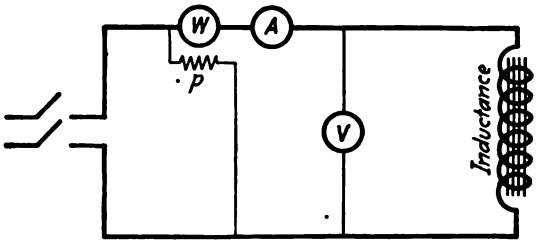


FIG. 83.

2. Determine the effective resistance from alternating-current measurements, and all data necessary to determine vector diagram. Be careful not to put more than rated current through coil.

3. Place some non-magnetic conductor in the coil to increase the effective resistance and determine the data for the vector diagram.

4. Replace the metal used in 3 by an iron core and repeat measurements made under 3.

In order to obtain accurate results it will be necessary to apply all instrument corrections. See pages 6 to 8.

Results Required.—

a. Calculate the self-inductance of the coil from the dimensions and the number of turns.

b. Construct vector diagrams representing conditions obtained in 2, 3, and 4.

Draw these vector diagrams to a convenient working scale and make them plenty large so that accurate results may be obtained.

Calculate and tabulate the following for each condition:

c. True self-inductance from vector diagrams.

d. Effective resistance from vector diagram.

e. Effective resistance as calculated from $\frac{P_0}{I_0^2}$.

f. Increase in resistance due to eddy currents from results obtained in *d*.

g. Calculate (*f*) using result obtained in (*e*).

h. Power factor as calculated from $\frac{P_0}{VI_0}$.

i. Magnetizing current from diagram.

j. Equivalent inductance by formula $L_e=\frac{1}{2\pi f}\sqrt{\left(\frac{V}{I_0}\right)^2-R_e^2}$.

k. Compare the results of (*a*), (*c*) and (*j*) and examine discrepancies.

LAWRENCE, "Principles of Alternating Currents," p. 234.

TIMBIE AND BUSH, "Principles of Electrical Engineering," p. 347.

JACKSON, "Alternating Currents and Alternating-Current Machinery," p. 400.

H. B. DWIGHT, "Some New Formulas for Reactance Coils," *Trans. A.I.E.E.*, 1919, p. 1675

33

POWER MEASUREMENTS IN THREE-PHASE CIRCUITS

This experiment is to illustrate the use of the two-wattmeter and three-wattmeter methods for measuring power in three-phase circuits, as well as to show the relative readings of the wattmeters in the two-wattmeter method under varying power factors. Either the two-wattmeter or three-wattmeter method will give the true power in a three-phase circuit whether the load is balanced or not, provided there is no neutral connection between the source of power and the load. The three-wattmeter method will give the true power under all conditions if the common junction of the potential coils of the wattmeters is connected to the neutral of the load.

Apparatus.—Three equal impedance coils and three equal non-inductive resistances, both sets having about the same current rating and each capable of withstanding full line voltage.

Procedure.—Connect the instruments in circuit as indicated by the diagram and read all instruments in each of the following:

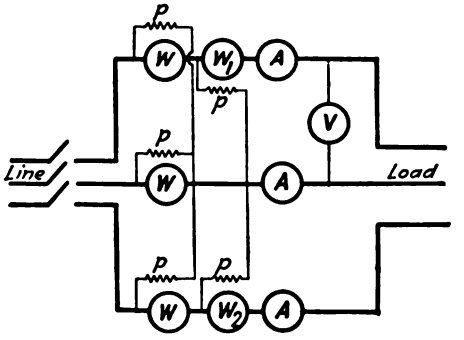


FIG. 84.

1. With the impedance coils connected in delta.

2. Repeat (1) with the coils in Y.

3. Replace the impedance coils with the resistance units connected in delta.

4. Repeat (3) with the load Y-connected.

5. Impedance coils in delta and resistances in delta.

6. Impedance coils in Y and resistances in delta.

7. Impedance coils in Y and resistances in Y.

8. Impedance coils in delta and resistances in Y.

9. Cut out one of the impedance coils in (5).

10. Cut out one of the resistances in (6).

11. Cut out one of the resistances in (7) and connect the junction of the remaining two resistances to the neutral of the source.

12. Cut out one of the impedance coils in (7) and connect the junction of the impedances to neutral of the source.

Results Required.—

a. Average resistance and reactance of the impedance coils calculated from readings taken in (1) and (2).

b. Average resistance of the resistance units calculated from readings taken in (3) and (4).

c. From values calculated in (*a*) and (*b*) calculate what each meter should read in case (5) and compare with actual readings.

d. Repeat (*c*) for case (6).

e. Repeat (*c*) for case (7).

f. Repeat (*c*) for case (8).

g. Repeat (*c*) for case (9).

h. Repeat (*c*) for case (10).

i. Repeat (*c*) for case (11).

j. Repeat (*c*) for case (12).

k. Calculate from the readings obtained in 1–8 inclusive, the power-factor in each case Plot P_1/P_2 vs. power factor.

l. Draw to scale vector diagrams representing conditions in each case.

m. Check the power in case (5) by using only one wattmeter.

n. Measure power in case (5) and compare with line meters, using 5 ampere 150-volt wattmeters and instrument transformers.

JACKSON, "Alternating Currents and Alternating Current Machinery," p. 359.

LAWRENCE, "Principles of Alternating Currents," p. 314.

DAWES, "Electrical Engineering," vol. II, p. 76.

HUDSON, "Engineering Electricity," chap. VIII.

TRANSFORMER EFFICIENCY AND REGULATION

Since the efficiency of a transformer at full load will seldom be below 95 per cent. and may be as high as 98 per cent. in large sizes, it is important, especially in competitive tests, that efficiency determinations be made with considerable accuracy. Any method involving a direct measurement of the output and the input and taking their ratio is practically worthless, since any error made in the determination of either of these enters directly into the result, i.e., the measured efficiency. Methods involving a direct determination of losses must be used. (See experiment on "Stray Power," page 134.)

The losses of a transformer can be separated into copper losses and iron losses. The first of these is made up of the I^2R losses in the primary and the secondary circuits. Primary refers to the side which receives electrical power and secondary to the side which delivers electrical power. Since a transformer may be used either to step up or step down voltage, either side may be primary or secondary. To avoid confusion the terms high-tension and low-tension sides will be used. The iron loss includes the eddy current and hysteresis losses in the iron core. These latter are dependent upon the frequency and the flux density in the iron core. The flux density is directly proportional to the voltage induced in the high-tension and low-tension sides. This depends upon the voltage impressed upon the transformer and varies but slightly with the load. Since this variation is small the core loss may be considered constant for any impressed voltage and frequency and independent of the load.

If the core loss and resistance of the high- and low-tension sides be measured, the efficiency at any load may be expressed as follows:

$$\eta = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{Losses}} = \frac{V_H I_H \cos\theta}{V_H I_H \cos\theta + P_{h+e} + I_H^2 R_H + I_L^2 R_L}$$

$$= \frac{V_L I_L \cos\theta}{V_L I_L \cos\theta + P_{h+e} + I_H^2 R_H + I_L^2 R_L}, \quad \ldots \quad (1)$$

where V_H and V_L are the high-tension and low-tension voltages respectively, I_H and I_L are the high-tension and low-tension currents respectively, R_H and R_L are the high-tension and low-tension resitances respectively and P_{h+e} the core loss.

Example.—A certain 15 kv.-a., 10 : 1 transformer with a 200-volt low-tension winding has the following constants:

$$R_H = 2 \text{ ohms},$$

$$R_L = 0.02 \text{ ohm}.$$

The core loss with 200 volts impressed on the low-tension winding or 2000 volts impressed on the high-tension winding is 150 watts. The low-tension current is $15000/200 = 75$ amperes. The high-tension current is $75/10 = 7.5$ amperes. This latter neglects the exciting current which can be neglected without producing sensible error in efficiency. Full-load efficiency at unity power factor is

$$\frac{15{,}000}{15{,}000 + 150 + 0.02(75)^2 + 2(7.5)^2} \times 100 = 97.6 \text{ per cent.}$$

The efficiencies at other loads may be found by using values of the current corresponding to the load for which the efficiency is desired. For example, the half load I_L should be $75/2 = 37.5$.

Measurement of the Core Loss.—The core loss in a transformer is independent of the side upon which the proper voltage is impressed but when measuring this loss it is usually more convenient and safer to supply the voltage to the low-tension side.

To determine the core loss, connect the low-tension side of the transformer through a switch to mains of proper frequency and voltage. The high-tension circuit should be open and *its terminals placed so that there is no possibility of coming in contact with them.* If the switch connecting the low-tension side to the mains is now closed the magnetization of the core will be that for which the transformer is designed, and the energy supplied will be equal to the core loss plus a very small I^2R loss in the low-tension side which will be entirely negligible. If a wattmeter is placed in circuit, its reading will be equal to the core loss of the transformer. A voltmeter and an ammeter should also be placed in circuit. The ammeter will give the exciting current of the transformer, while the voltmeter will serve to show whether the proper voltage is supplied to the transformer.

The connections are shown in Fig. 85. The auto-transformer shown is used to control the voltage impressed on the transformer under test. It has a number of voltage taps brought out on its secondary side, any pair of which may be connected to the transformer being tested by means of two dial-type switches.

The size of a wattmeter is always determined by the volt-amperes to be measured and never by the true watts. Therefore the wattmeter used for the connection shown above must have a potential coil which will stand the rated voltage of the low-tension side of the transformer. It must have a current coil which will carry the exciting current of the transformer. The exciting

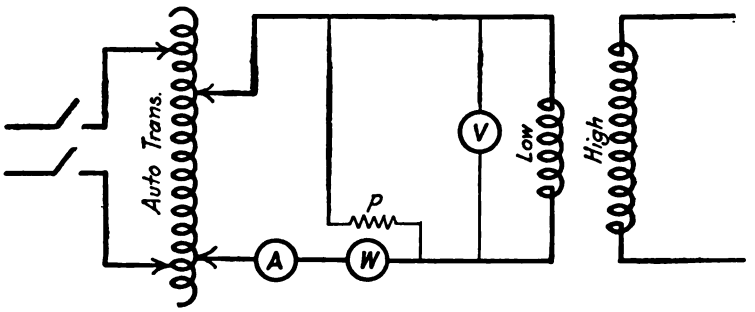


FIG. 85.

current of a transformer generally will be between 1 and 5 per cent. of the full-load current. See table of losses, page 29.

Copper Losses.—The copper losses may be found from the resistances of the low- and high-tension sides as already indicated. They may also be found by short-circuiting either the low- or high-tension side of the transformer and applying sufficient voltage to the other side to force full-load current through the coils. In a well designed transformer the voltage required for this test ought not to be over 5 per cent. of the rated voltage of the side upon which the voltage is impressed and it will generally be less. The better side to short-circuit depends upon the size of the instruments and the voltage supply available. The low-tension side is usually short-circuited.

The power supplied on short-circuit will be for the high- and low-tension copper losses and a very small core loss which is negligible. The proper connections for the short-circuit run are shown in Fig. 86.

The voltage of the mains need not be more than 5 per cent. of the rated high-tension voltage of the transformer. The wattmeter should have a current coil which will carry the rated high-tension current of the transformer without overheating. It should have a potential coil for a voltage of at least 5 per cent. of the rated high-tension voltage of the transformer. The auto-transformer should first be set for lowest voltage, then the switch connecting the transformer to the mains should be closed. Then adjust the auto-transformer slowly, increasing the voltage impressed on the transformer until ammeter A indicates full-load current. Wattmeter W will then indicate full-load copper loss in both windings of the transformer plus the meter losses.

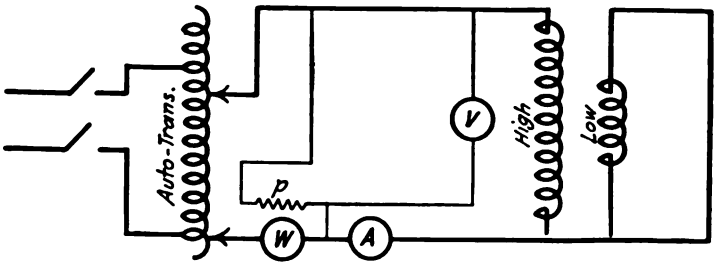


FIG. 86.

The copper loss P_{Cu} is equal to the total I^2R loss in the transformer since full-load current flows in both sides. Since the ratio of high-tension to low-tension current in a transformer is sensibly constant, the total copper loss will vary as the square of either the high-tension or the low-tension current. This loss is therefore equal to a fictitious resistance, known as the equivalent resistance, multiplied by the square of either the high-tension or low-tension current according to whether this resistance is referred to the high-tension or the low-tension side of the transformer.

$$P_{Cu} = I_H^2 R_H + I_L^2 R_L,$$

and

$$\frac{I_L}{I_H} = \frac{V_H}{V_L} = a,$$

where a is the ratio of transformation. Then

$$P_{Cu} = I_H^2 (R_H + a^2 R_L) = I_H^2 R_{eH},$$

or

$$P_{Cu} = I_L^2 (R_H/a^2 + R_L) = I_L^2 R_{eL},$$

from which

$$\frac{R_{eH}}{R_{eL}}=a^2. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

This resistance is referred to the high- or low-tension side, according as high-tension or low-tension current is used in finding it. The two values of an equivalent resistance of a transformer will be to each other as the square of the ratio of transformation of the transformer. The relation between the equivalent resistances also holds for the equivalent reactances and impedances. The total copper loss for any load may be found by multiplying the equivalent resistance by the square of the current (low or high tension according to the value of the equivalent resistance used) corresponding to the given load. The efficiency may be calculated as follows:

$$\eta=\frac{V_HI_H\cos\theta}{V_HI_H\cos\theta+P_{h+e}+I_H^2R_{eH}}=\frac{V_LI_L\cos\theta}{V_LI_L\cos\theta+P_{h+e}+I_L^2R_{eL}}. \quad (3)$$

The voltage, V_z, required to force full-load current through the transformer on short-circuit is used up in overcoming the total impedance drop in the transformer, and is, therefore, numerically equal to the equivalent impedance Z_e of the transformer multiplied by the current I.

$$V_z=IZ_e,$$
$$Z_e=V_z/I.$$

Z_e as well as the equivalent resistance may be referred to either the high-tension or low-tension side of the transformer. If the low-tension side is short-circuited, V_z will be the measured voltage on the high-tension side and

$$V_{zH}=I_HZ_{eH},$$

where I_H is the current in the high-tension side with the low-tension side short-circuited and Z_{eH} is the impedance of the transformer referred to the high-tension side.

This impedance, Z_{eH}, is the vector sum of the resistance R_{eH} (found from the short-circuit run) and the reactance X_{eH} referred to the high-tension side of the transformer. These vectors are at right angles to each other. Therefore:

$$Z_{eH}=\sqrt{R_{eH}^2+X_{eH}^2},$$

from which

$$X_{eH}=\sqrt{Z_{eH}^2-R_{eH}^2}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The regulation of a transformer is defined as the ratio of the rise in voltage, when a full load of specified power factor is thrown off, to the full-load voltage.

With X_{eH} and R_{eH} known, the regulation of the transformer can be easily calculated from the simple transformer diagram. Fig. 87 represents the diagram for a non-inductive load, all values being referred to high-tension side.

In this case V_H and $I_H R_{eH}$ are in phase since the load is non-inductive. From the figure it follows that:

$$aV_L = \sqrt{(V_H + I_H R_{eH})^2 + (I_H X_{eH})^2}, \quad . \quad . \quad . \quad (5)$$

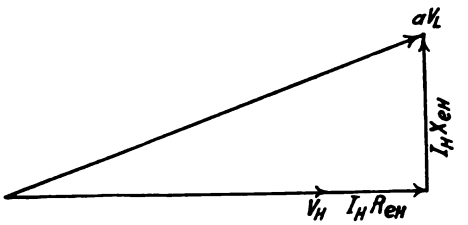


FIG. 87.

assuming the power to be supplied to the low-tension side. aV_L is the high-tension voltage at no load.

The regulation is given by:

$$\frac{aV_L - V_H}{V_H} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Example.—Suppose that the value of X_{eH} for the transformer used in the example on page 200 was found to be 8 ohms and that R_{eH} was found from the short-circuit run to be 4 ohms. Assume that the transformer is used to step up the voltage and has a voltage impressed upon its low-tension side such that its terminal voltage on its high-tension side under a full non-inductive load is $2000 = V_H$. The full-load high-tension side current is 7.5 amperes.

$$aV_L = \sqrt{(2000 + 7.5 \times 4)^2 + (7.5 \times 8)^2} = 2031.$$

The regulation is $\frac{2031 - 2000}{2000} \times 100 = \frac{31}{2000} \times 100 = 1.55$ per cent.

This means that when full load is thrown off the voltage rise on the high-tension side is 31 volts or 1.55 per cent. The same result

would have been obtained if values of X_{eL} and R_{eL} referred to the low-tension side had been used. Considering the general case, where the power factor is cos θ, the equation becomes

$$aV_L = \sqrt{(V_H \cos \theta + I_H R_{eH})^2 + (V_H \sin \theta + I_H X_{eH})^2}. \quad (7)$$

$$\text{Regulation} = \frac{aV_L - V_H}{V_H},$$

and, referring everything to the low-tension side

$$V_L = \sqrt{\left(\frac{V_H}{a} \cos \theta + I_L R_{eL}\right)^2 + \left(\frac{V_H}{a} \sin \theta + I_L X_{eL}\right)^2}, \quad (8)$$

which is simply equation (7) divided by a.

$$\text{Regulation} = \frac{V_L - \frac{V_H}{a}}{\frac{V_H}{a}}, \quad (9)$$

which is merely equation 6 with both numerator and denominator divided by a. In this case 200 would have been used for $\frac{V_H}{a}$ and 75 for I_L.

In case the load is taken from the low-tension side equation (7) becomes

$$\frac{V_H}{a} = \sqrt{(V_L \cos \theta + I_L R_{eL})^2 + (V_L \sin \theta + I_L X_{eL})^2}.$$

Procedure.—If the low-tension winding is in two sections they must first be connected in series, i.e., so that the ampere-turns of the two coils at any instant tend to cause a flux in the same direction. To test for this condition connect the coils as shown in Fig. 88. Impress not more than the normal voltage upon either coil and measure the total voltage across the two. For the proper connection the voltage across the two coils should equal twice that impressed on *ab*. If the connections are wrong this voltage will be zero, and is the proper condition for parallel connection. The proper connections of high-tension sides may be made similarly.

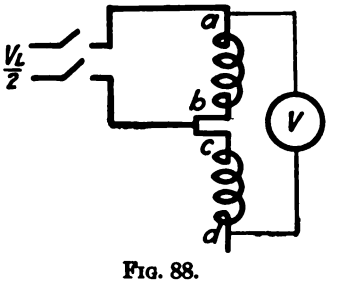


FIG. 88.

Connect up as shown in Fig. 86, putting an auto-transformer in circuit so that the voltage may be adjusted. When the connections are properly made short-circuit the ammeter and wattmeter current coil, and close the switch. Adjust the voltage to rated value and read all three instruments. The corrected wattmeter reading will be the core loss.

Disconnect the transformer and connect as shown in Fig. 87, supplying voltage to the high-voltage side. Set the switches on the auto-transformer for minimum voltage. Short-circuit the ammeter and wattmeter and close the main switch. Increase voltage until full-load current flows in the high-tension side, then read all instruments.

Results Required.—

a. Curve of open-circuit core loss and volts.

b. Curve of ratio of transformation plotted against volts.

c. Curve of short-circuit current and volts.

d. Equivalent resistance calculated, first from short-circuit run and second from measured ohmic resistances.

e. Equivalent reactance.

f. Calculated regulation at full-load unity power factor and full-load kilowatt output, 0.8 power factor, leading and lagging currents.

g. Calculated efficiency curve to 25 per cent. overload current at unity power factor.

h. Calculated efficiency curve to 25 per cent. overload current at 0.8 power factor, lagging current.

i. Calculated efficiency curve to 25 per cent. overload current at 0.8 power factor, leading current.

j. Explain the effect of leading and lagging currents upon the regulation and efficiency of a transformer supplying a definite kilowatt output.

k. Can the temperature rise in a transformer at full load be determined by short-circuiting one side and adjusting impressed voltage on the other side until full-load current flows?

l. It is desired to operate a 25-cycle transformer on 60 cycles, the same voltage being applied in each case. Determine the full-load iron losses and copper losses for the two frequencies. Calculate the efficiencies for unity and 0.8 power factor at full-load current. Assuming the iron losses to be constant for varying load, calculate

at what load the maximum efficiency will occur in each case. Calculate hysteresis and eddy currents constants.

m. A transformer is required to operate at voltages ranging betwcen 10 per cent. above and 10 per cent. below rated voltage. Assuming total losses at full load must remain constant at normal full-load rated voltage unity power factor value, take necessary data and calculate the curve showing the relation between rating in kv-a. and per cent. of rated voltage. Also plot curve showing relation between rated current and per cent. of rated voltage.

n. Determine the "*T*" network of the equivalent one to one transformer and from it compute the regulation and efficiency.

o. Using a transformer with four equal coils compare regulation and efficiency when operating as a regular transformer and as an auto-transformer with a 2 : 1 ratio. How do the ratings compare?

HUDSON, "Engineering Electricity," ch. 14.

LAWRENCE, "Principles of Alternating-Current Machinery," pp. 151–212.

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W. W. LEWIS, "Losses in Transformers," *Trans. A.I.E.E.*, 1913, p. 439.

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35

TRANSFORMER HEAT RUN AND EFFICIENCY TEST BY THE OPPOSITION METHOD

In order to test a transformer for its rise in temperature under load, it is necessary to operate it under normal conditions of flux and current for sufficient length of time for it to reach its ultimate temperature. Although a transformer which is used for lighting purposes will seldom be run at full load long enough to reach its final temperature, a knowledge of the final temperature is, nevertheless, important.

A run of eight hours will generallly be sufficient except in the case of large transformers which are built for power purposes. A simple way of making a heat run on a transformer is to supply the proper voltage to one side and load the other with any suitable artificial load until it delivers full-load current. If a large transformer is to be tested by this method, the cost of the power consumed will be an important item.

Whenever two similar transformers are available, the following opposition method is economical of power and satisfactory. Data may easily be obtained during the test, from which the efficiency under full-load conditions may be calculated with accuracy. The rate at which the temperature rises may also be obtained.

For the opposition test of two transformers, the low-tension sides of the transformers are connected in parallel and power is supplied to them at their rated frequency and voltage. If the high-tension sides are on open circuit, the power supplied to the low-tension sides will be the core losses of the two transformers plus a negligible copper loss. If the high-tension sides are now connected in parallel (like terminals together), no current will flow through them since their voltages at every instant will be equal and opposite. The conditions, in so far as the low-tension sides are concerned, are unaltered by closing the high-tension circuit, provided the voltages are in opposition.

Fig. 89 shows, diagrammatically, the low-tension sides of the two transformers in parallel with the high-tension sides in parallel or series opposition.

The plus and minus signs indicate the voltage relations in the system at the instant when the upper ends of the low-tension sides, as shown in the figure, are positive.

The low-tension sides are in parallel since like terminals are connected together and to the same main. If the low-tension sides are now disconnected from the source and a voltage is impressed across one of the high-tension windings, the second high-tension winding being in parallel with the first as before, equal voltages will be induced in the low-tension windings and with respect to their own series circuit they will be in opposition and consequently no current will flow in them. If, however, the voltage instead of being impressed on the high-tension sides in parallel is inserted in the high-tension circuit as at *A*, the polarity of one of the high-tension windings will be reversed with respect to the other, which in turn will cause the polarity of the corresponding low-tension winding to be reversed with the result that the two voltages in the low-tension windings will be aiding and current will flow. This current will be limited only by the impedances of the transformer windings.

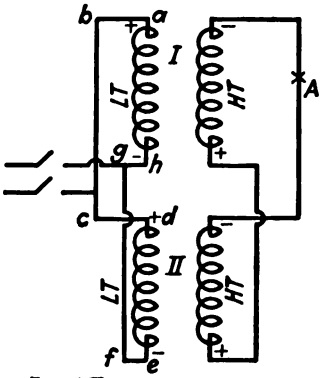


FIG. 89.

If then at *A*, an electromotive force be introduced such as to cause full-load current in the high-tension sides, full-load current will also be produced by induction in the low-tension sides. This current in the low-tension sides will not enter the external circuit but will simply circulate through the closed circuit, *abcdefgh*, formed by the low-tension coils. As far as the high-tension sides are concerned, the low-tension sides are virtually short-circuited. It follows that the power supplied at *A* to maintain the full-load current in the transformers is the total copper loss of both transformers since the power supplied to any short-circuited trans-

former is, with the exception of a negligibly small core loss, all used up in this way.

The core loss can then be supplied through the low-tension sides while the copper loss can be supplied through the high-tension sides by inserting one side of a third transformer in the high-tension circuit at A, and raising the voltage impressed on this third transformer until full-load current exists in the transformers under test. The circuit instead may be broken at A and connected to the mains through a suitable resistance, but the use of a third transformer is better, because there is then no metallic con-

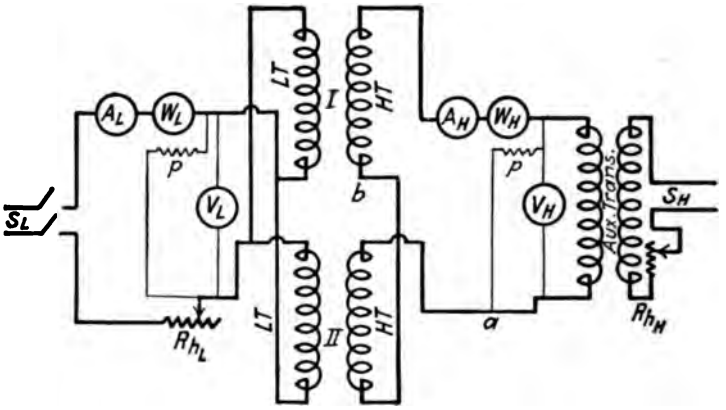


FIG. 90.

nection between the high-tension windings and the laboratory mains.

The voltage at A which will produce the full-load current in the transformers under test is approximately equal to twice the impedance voltage of one transformer measured on the high-tension side. This total voltage for the two transformers generally will not be over 10 per cent. of the rated high-tension voltage of one.

The complete connections for the opposition test of two transformers are shown in Fig. 90.

Wattmeters, W_L and W_H, give the core and copper losses, respectively, of both transformers. Ammeter A_L indicates the sum of the no-load currents of the two transformers while A_H shows the high-tension load current carried by each of the transformers and serves to show when the conditions of full load have been attained. Voltmeter, V_H, gives twice the impedance volt-

age of a single transformer and also serves to show what voltage is being impressed on the potential coil p of wattmeter W_H. Voltmeter V_L is used to indicate whether the proper voltage is being applied to the transformers.

Wattmeter W_L should have a potential coil for a voltage equal to the low-tension voltage of the transformers under test. Its current coil should have capacity to carry twice the no-load current of one transformer or from 2 to 10 per cent. of the full-load low-tension current of one transformer. (See table of losses, page 29.)

Procedure.—A third transformer should be used to supply the copper losses of the transformers under test. Any transformer which will give a voltage equal to twice the impedance voltage of the two transformers under test and a current equal to the high-tension current of one of these will answer.

As a matter of protection all the high-voltage terminals of the transformers should be placed in a box. The cover of this box should be arranged to break all the low-voltage circuits of the transformers when it is opened and consequently make the high-voltage terminals dead. No wires should be brought out through the cover of the box.

There are a number of ways of testing for opposition of the high-tension windings. If a high-range voltmeter is not available, the following methods are simple and perfectly satisfactory.

Make all the connections as in Fig. 90.

Care must be taken not to get the potential coil of wattmeter W_H across high voltage. This will occur, if by mistake the terminal a of the potential coil is connected to b. Such a connection will cause the instrument to be burned out instantly. Care must also be taken to see that the current coil is connected next the auxiliary transformer and not between the transformers as at b.

Now close S_H, leaving S_L open. If the connections are correct, the low-voltage side will be short-circuited with respect to the high-voltage side, and full-load current as indicated by A_H will flow for a voltage of less than 10 per cent. of normal voltage on the high-tension side. The reading of the voltmeter V_L may also be used as an indication of correct connection in this last method. If the low-pressure coils are properly connected, there will be no voltage impressed on V_L while if the connections are incorrect, the voltage will equal the voltage impressed on either of the high-voltage sides divided by the ratio of transformation. Unless the

ratio of transformation is low the reading of the voltmeter V_L will be too small to give a reliable test. The indication of the ammeter should be used.

The amount of resistance necessary in Rh_H will depend upon the rating of the transformers tested and the ratio of transformation of the auxiliary transformer.

Another test may be made as follows: Connect high-tension sides in series at random and excite the low-tension side of one transformer with approximately rated voltage. The voltage induced in the low-tension side of the other transformer will then equal the voltage impressed on the low-tension side of the first. Since these low-tension sides are to be connected in parallel, connect one side of the low-tension winding of the second transformer to one of the mains and test for zero voltage between the remaining terminal of this transformer and the other main. If this voltage is not zero but twice the voltage across one transformer the low-tension lead which was first connected to a main should be connected to the other main.

When the connections have been properly made and tested for opposition on the high-tension side, close S_L and adjust the resistance in Rh_L until the rated voltage of the transformers under test is impressed on their low-tension windings. This will be shown by the reading of V_L.

Now adjust Rh_H for maximum resistance, and close S_H. Gradually decrease the resistance in Rh_H until full-load current exists in the high-tension sides. This condition will be shown by the reading of ammeter A_H. Full-load current will also flow in the low-tension sides.

The transformers will now be carrying full-load current and will be fully excited and therefore will be under the full-load conditions. The only power supplied to the system, however, will be that for the core and the copper losses of the two transformers under test. The core and copper losses of the two transformers will be indicated on the wattmeters W_L and W_H respectively. Read all instruments periodically until the end of the test.

The transformers should be kept under the conditions of full load for a sufficient length of time for them to reach their final temperature. This generally will require in the neighborhood of eight hours. The temperature of the oil should be measured at the beginning and end of run.

The rise in temperature may be calculated, as indicated in the experiment on "Heat Run on a Direct-current Dynamo," from the equivalent resistance of the transformers obtained at the beginning and the end of the test.

The equivalent resistance of the transformer (for the meaning of this term see previous experiment) can be obtained from the readings of W_H and A_H. $\frac{P_H}{2}$ is the copper loss of one transformer. This is equal to $I_H^2 R_{eH}$ where R_{eH} is the equivalent resistance of the transformer referred to the high-tension side and I_H is the high-tension current given by the ammeter A_H.

Due to the fact that the wattmeter will be reading on a poor part of its scale on account of low-power factor, it is more accurate to calculate the rise of temperature from the resistances of the transformer obtained by the drop of potential method, immediately before and after the test.

Since it is possible to obtain the rise in temperature from the wattmeter reading, a curve of rise of temperature with time may be plotted provided readings of W_H and I_H are taken at regularly timed intervals during the test.

The full-load efficiency of the transformers under test will be given by the rated output divided by their rated output plus their full-load copper and core losses.

$$\text{Efficiency} = \frac{\text{Rated Output}}{\text{Rated Output} + \text{core loss} + \text{full-load copper loss}}$$

$$= \frac{\text{Rated Output}}{\text{Rated Output} + \frac{P_L}{2} + \frac{P_H}{2}},$$

where P_H and P_L represent the corrected readings of the two wattmeters when the transformers are under full-load conditions. See page 8 for method of making instrument corrections.

Since the core loss is practically constant and the copper loss varies as the square of the current, the efficiency at any load may be easily found.

For example: The efficiency at half load will be

$$\frac{\text{Output for } \frac{1}{2} \text{ load}}{\text{Output for } \frac{1}{2} \text{ load} + \frac{P_L}{2} + \left(\frac{1}{2}\right)^2 \left(\frac{P_H}{2}\right)}.$$

Results Required.—

a. Temperature rise in each coil, of one transformer resulting from a heat run of two or three hours duration, calculated from hot and cold ohmic resistances.

b. Curve of temperature rise in the copper, obtained from equivalent resistance measurements made during the run. (These resistances are to be determined from wattmeter readings. The wattmeter readings *must* be corrected for instrument losses.)

c. Efficiency curve plotted from data taken at one, two, three, and four quarters of full-load, unity power factor. Calculate the efficiency at one-eighth load.

d. Temperature rise in the oil.

e. What would be the effect on the all-day efficiency of a given transformer if the number of turns on the transformer were doubled and the cross-section of the core halved?

f. Assuming current and voltage rating to remain the same, why is the ratio of effective to ohmic resistance so much smaller in the transformer than in the synchronous generator?

g. Calculate the all-day efficiency for a lamp load assuming the transformer to be fully loaded for one hour, to carry 1–2 load for 2 hours, 1–4 load for 3 hours, and to be zero load the rest of the time.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. II, p. 67.

LAWRENCE, "Principles of Alternating-Current Machinery," p. 218.

S. E. JOHANNESEN and G. W. WADE, "Methods of Determining Temperature of Transformers and of Cooling Medium," *Trans. A.I.E.E.*, 1913, p. 191. Other valuable articles on the temperature measurements of transformers will be found elsewhere in this volume.

36

CONSTANT-CURRENT TRANSFORMER

A sketch of a constant-current transformer is shown in Fig. 91. Either series incandescent lamps or resistance will be used for a load. *C* is the iron core, *PP* the primary[1] coil, and *SS* the secondary coil. The secondary coil is movable and is hung from an arm (not shown) which is nearly counterbalanced by a set of counter-weights.

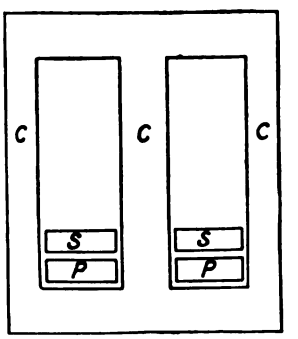


FIG. 91.

The counter-weights are arranged so that when the transformer is delivering its maximum output the primary and secondary coils are in contact. Under these conditions the leakage reactance is small. Any increase in the secondary current due to the short-circuiting of the lamps forming the load will produce an increased repulsion between the coils and cause them to move apart. This increases the leakage reactance and cuts down the current. It is possible, by properly adjusting the length of the arm which carries the counter-weights, to have the transformer maintain automatically nearly constant current in the secondary circuit from full load down to no load. The weight of the counter-weights determines the secondary current for which the transformer regulates.

Procedure.—The object of the experiment is to determine the characteristic curves and limits of regulation of the transformer when used on a non-inductive load consisting either of a bank of series incandescent lamps or non-inductive resistance.

The proper connections for the transformer are shown in Fig. 92.

[1] In this experiment primary will refer to the side which receives electric power at constant voltage and secondary to the side which delivers power at constant current.

The subscripts P and S refer to primary and secondary respectively. Since the load is practically non-inductive, no secondary wattmeter is required.

After having connected the transformer as shown in the diagram, short-circuit the secondary as well as the ammeters and wattmeter, raise the secondary coil to its highest position and close the main switch.

Apply load until the secondary begins to float and note secondary current. Put on full load and note secondary current. If the two currents are not equal, adjust balance-sector until they are equal and then adjust balance weight until rated current is obtained

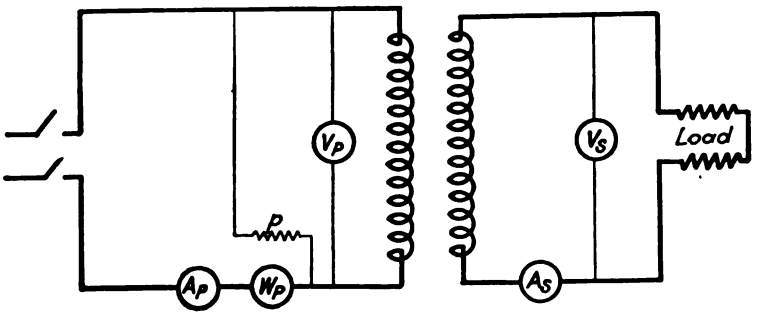


FIG. 92.

at the extreme positions of the secondary coil. Now vary the load from short circuit to open circuit taking readings of all instruments at 10 or 12 points, being sure that from 4 to 6 of these points are within the range of automatic regulation.

Results Required.—

a. Curve of primary power factor against output.

b. Curve of efficiency against output.

c. Curve of primary amperes against output.

d. Curve of secondary amperes against output.

e. Curve of secondary volts against output.

f. Draw to scale vector diagrams representing conditions at full load and at short circuit.

LAWRENCE, "Principles of Alternating-Current Machinery," p. 226.

CHRISTIE, "Electrical Engineering," p. 318.

GRAY, "Principles and Practice of Electrical Engineering," 2nd Ed. p. 267.

37

THREE-PHASE TRANSFORMER CONNECTIONS

This experiment is to illustrate the different voltages obtained by the use of three similar transformers in connection with a three-phase system. The transformers should have four like coils each.

The experiment will consist of connecting the transformers in several possible ways for three-phase connections and measuring the voltages obtained.

The different transformer connections are given below together with a diagrammatic representation of the connections. The voltages are also indicated, assuming that 2:1 transformers, with 230 volts applied to primary or high-tension sides, are used.

a. Primaries in △.
Secondaries in △.

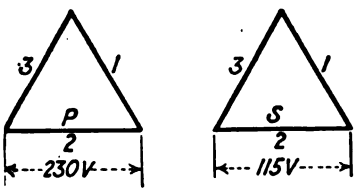


FIG. 93.

When transformers are connected as shown in *a*, the burning out of one of the three transformers will not interrupt the service. The remaining two will supply a three-phase load with a maximum capacity (for the same heating) of 58 per cent. of that of the three transformers.

b. Primaries in △.
Secondaries in Y.

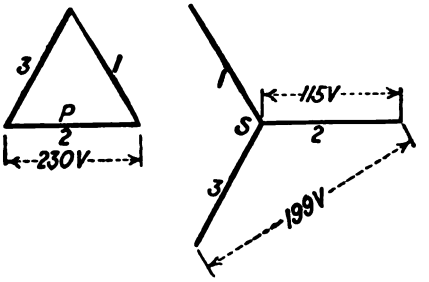


FIG. 94.

This arrangement with grounded neutral is used to step up the line voltage for transmission and yet have the same stress per transformer. For example, let the transformers be connected 1:2 with the low-tension sides in △ and 115 volts applied. With the secondaries in Y we get 398 volts for line voltage.

c. Primaries in Y.
Secondaries in Y.

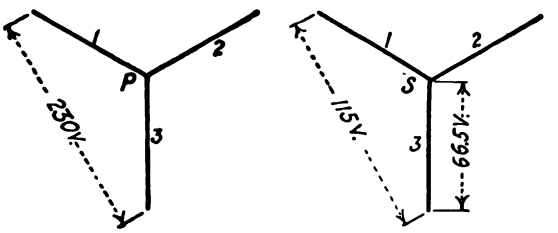


FIG. 95.

The 66.5 volts between the lines and neutral on the secondary side cannot be used unless a neutral is also used on the primary side or the transformers have a common iron core. Connection *c* without primary neutral can be used only for balanced loads, and in this case the three transformers must be identical.

d. Primaries in Y.
Secondaries in △.

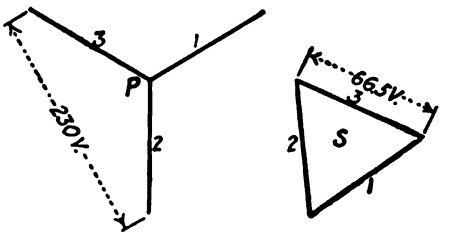


FIG. 96.

This is the reverse case of (*b*).

If the connections for secondaries in delta under Part *d* are made with the switch in the primary neutral open, it will be found impossible to connect the secondaries in any way which will make the voltage across the final gap zero as under Part *a* with the primaries in delta. The voltage across the gap is chiefly due to a third harmonic caused by opening the primary neutral switch. It will disappear if this switch is closed. Opening the primary neutral switch suppresses the third harmonic which should exist in the primary exciting currents and causes a third harmonic in the fluxes and consequently in the induced voltages. The third harmonic voltage across the gap may be as large as 40 to 75 per cent. the rated voltage on one transformer.

e. This is the so-called V-connection and is the same as *a*, with one transformer removed.

If the transformers have more than one primary and secondary connect these in series or parallel to get desired ratio.

Procedure.—First connect each transformer with its primaries in series and its secondaries in parallel. The simplest method of doing this is as follows: Take each transformer separately. Connect the two coils which are to be used as primaries together as shown in Fig. 97, and apply rated voltage or less to one of them. If the coils are properly connected to put them in series, a voltmeter placed across *a* and *c*, Fig. 97, will indicate twice the voltage applied to the

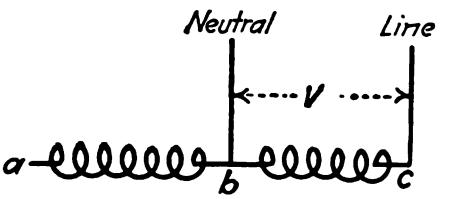


FIG. 97.

single coil *bc*. If the voltmeter reads zero reverse the coil *ab*. If it is desired to put the coils *ab* and *bc* in parallel, they should be connected so that the voltage between *a* and *c* is zero. The points *a* and *c* may then be connected together, putting the coils in parallel.

Having connected the primaries as desired, connect them to mains of proper voltage and connect one terminal of each secondary together and measure the voltage between the two free terminals. If this voltage is zero the free ends may be connected together and the coils will be in parallel. If the voltage between the free ends is double that between the terminals of a single secondary coil the secondaries will be in series.

a. Primaries in $\triangle$.
Secondaries in $\triangle$.

Connect the primaries in $\triangle$ and to the mains, then connect one end of each of two of the secondaries together. The voltage between the free ends will be either secondary voltage of one transformer or the square root of three times it. If it is the latter, reverse the connections of one of the secondaries. Now connect one end of the remaining secondary to one of the free ends of the other two. The voltage across the gap will now be zero or twice secondary voltage of one transformer. If it is the latter reverse the connections of the third secondary. The gap may now be closed, putting the secondaries in $\triangle$.

Measure the secondary and primary voltages, then apply a load to any one phase, so that full-load current flows in the most heavily loaded coil and measure voltages. Use double subscript notation in data.

Open the main switch and remove one transformer. This will leave the remaining two connected in V. Measure the voltages with the load across one transformer and then with load across the gap.

b. Primaries in $\triangle$.
Secondaries in Y.

In all Y connections measure voltages to neutral as well as between the lines.

Again connect the primaries in $\triangle$, then connect one end of two of the secondaries together. For Y-connection, the voltage between the free ends of the two secondaries should be $\sqrt{3}$ times secondary voltage. If it is not, reverse the connections of one of

the secondaries. Now connect one end of the secondary of the third to the common connection between the other two. If the voltage between the free end of this last secondary and the free end of either of the other two is not $\sqrt{3}$ times secondary voltage, reverse the connections of the last secondary. The secondaries will now be connected in Y.

Measure all voltages, then apply a single-phase load across any two lines and read voltages and current. Try also with load to neutral.

c. Primaries in Y.
Secondaries in Y.

Connect the primaries in Y, then connect the point of common connection of the primaries through a switch, which may be opened independently of the main switch, to the neutral wire of the supply system. Connect the secondaries in Y, following the directions given under *b*. Measure the voltages, both across lines and to neutral at no load and with a single-phase load. Then load to neutral. Try the effect of opening the switch in the primary neutral for this last condition. Take readings under all conditions.

d. Primaries in Y.
Secondaries in $\triangle$.

Disconnect the secondaries, then connect them, following the directions under *a*.

With the neutral switch on the primary side closed, measure the primary and secondary voltages. Load the system with a single-phase load. Note the effect on the system when loaded with a single-phase load, of opening the neutral switch on the primary side.

Results Required.—

Tabulate the no-load voltages, and the voltages for a single-phase load large enough to draw full-load current from the most heavily loaded coil for the following connections:

a. Delta to delta.
b. Delta to Y.
c. Y to Y.
d. Y to delta.
e. Y to delta with neutral.

f. Delta to Y, load to neutral.

g. Y to Y with primary neutral.

h. Y to Y with primary neutral and load to neutral

i. V to V.

j. Connecting two of the transformers for 230–230 volts) with coils in series), make measurements with T to T, three-phase to three-phase transformation.

k. With primaries and secondaries connected in T for a two-phase four-wire circuit.

l. How determine if voltages are in quadrature in the three-phase to two-phase connections.

m. What should be the ratio of turns for the Scott connection?

n. How can a neutral be obtained in (*j*) when the transformers have this proper ratio?

o. Draw vector diagrams (to scale), representing the load conditions of (*a*), (*c*), and (*h*). Represent the no-load conditions of (*i*) and (*j*). Show the coil and line voltages in the Y connections and the coil and line currents in the delta conditions. Equivalent impedances may be used.

p. Connect three single-phase transformers in Y on the primary side and delta on the secondary, with no load attached. Determine wave form of:

(1) Primary line current.
  (1*a*) Delta open.
  (1*b*) Delta closed.
(2) Secondary circulating current when delta is closed.
(3) Line and coil voltages in (1).
(4) Voltage across open delta in (1*a*).
(5) Repeat (1), (2), (3), and (4) with primary neutral connected. Also get neutral current and wave shape.

q. Determine the phase rotation of the mains.

LAWRENCE, "Principles of Alternating-Current Machinery," p. 252.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. II, p. 89.

JACKSON, "Alternating Currents and Alternating-Current Machinery," p. 546.

F. O. BLACKWELL, "Wye- or Delta-Connection of Transformers," *Trans. A.I.E.E.*, Vol. 22, 1903, p. 385.

R. W. SORENSEN and W. L. NEWTON, "Inherent Voltage Relation in Y and Delta Connection," *Trans. A.I.E.E.*, 1914, p. 711.

38

POLYPHASE TRANSFORMER CONNECTIONS

In the previous experiment, the problem of the transformation of polyphase power by means of three single-phase transformers was discussed. The three single-phase transformers had three independent magnetic circuits. Polyphase transformers are built with a single magnetic circuit as shown below:

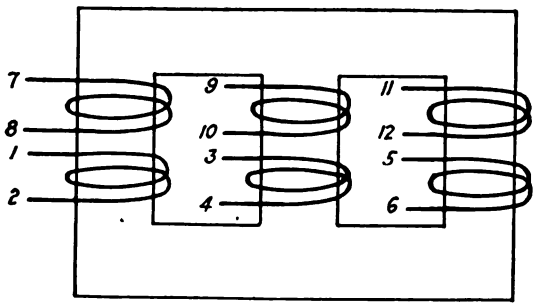


FIG. 98.

Such a transformer will have a smaller core loss, due to less volume of iron resulting from a shorter mean length of magnetic circuit than will three single-phase transformers of the same total rating.

A polyphase transformer may be connected in wye or delta just the same as may single-phase transformers. In this case, however, the primaries may not be connected at random but must be tested for proper connections. Assuming wye connection, similar points 2, 4 and 6 are connected, and 1, 3 and 5 go to the line. For delta connection we connect dissimilar ends of coils as 2–3, 4–5, and 6–1. In either case, if ϕ_{12} ($\phi_{12} = O$ when $V_{12} = \max.$) is a maximum, then we have the real part of ϕ_{34} negative and equal to $\frac{1}{2}\phi_{12}$ and the real part of ϕ_{56} negative and equal to $\frac{1}{2}\phi_{12}$.

This means that 1 2 carries full flux and 3 4 and 5 6 each carry ½ full flux in the opposite direction.

To test for wye connection we connect any two points, presumably 2 and 4, and apply normal voltage for the two coils to the free ends. If we have made the connection correctly, we have a flux downward in 1 2 and upward in 3 4 and therefore zero voltage across 5 6. If we have it wrong we get a flux down through 1 2 and 3 4 and thus twice this flux through 5 6 and therefore the same voltage across 5 6 as we apply to 1 2 and 3 4 in series. This means that 3 4 should be reversed. It also indicates proper arrangement for delta connections.

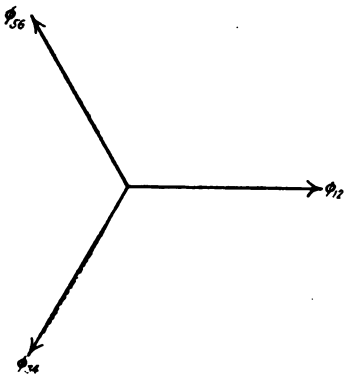


FIG. 99.

The next step for the wye connection consists in connecting 4 and 6, applying voltage to 3 5 and testing for zero voltage between 1 and 2. If this is not zero the connections of 5 6 are reversed and the transformer is in wye, and a three-phase voltage may be applied to terminals 1, 3 and 5.

To connect in delta, connect 2 and 3, apply normal voltage to 1-4 and test for normal voltage between 5 and 6. Next connect 4–5 applying normal voltage to 3-6 and test for normal voltage between 1 and 2. If this is found, 1 may be connected to 6 and a three-phase voltage may be applied to the three junction points.

The connection of the secondaries in wye or delta is the same as was described in experiment 37.

In case the secondary is divided into two sections a six-phase star system will result if the mid points of the three secondaries are interconnected.

A six-phase mesh connection may be obtained if the secondaries are connected in double delta. In this case the second delta is closed in the reverse order from the first. To do this connect secondaries on each transformer in parallel, then connect in delta.

This gives similar connections. Now remove one set of secondaries and reconnect in the reverse order.

Assume transformer with four equal coils per phase and connected with primaries in series and secondaries in series. For the following connections we get the following ratios of transformation:

Δ–Δ	1 : 1
Δ–Y	$1 : \sqrt{3}$
Y–Y	1 : 1
Y–Δ	$1 : 1/\sqrt{3}$
Δ–six-phase star	$1 : \frac{1}{2}$
Δ–six-phase mesh	$1 : 1/\sqrt{3}$
Y–six-phase star	$1 : \frac{1}{2\sqrt{3}}$
Y–six-phase mesh	$1 : \frac{1}{3}$

Procedure.—Connect both primaries and secondaries in series if they are provided with two coils each.

a. Connect primaries in delta and secondaries in delta and measure voltages at no load and under a single-phase load large enough to draw rated current from the most heavily loaded coil.

Repeat for the following conditions:

(*b*) delta-wye.
(*c*) delta-wye load to neutral.
(*d*) wye-delta.
(*e*) wye-delta with primary neutral.
(*f*) wye-wye.
(*g*) wye-wye with load to neutral.
(*h*) wye-wye with primary neutral and load to neutral.
(*i*) wye-six-phase star.
(*j*) wye-six-phase mesh.
(*k*) delta-six-phase star.
(*l*) delta-six-phase mesh.
(*m*) Measure equivalent resistance and impedance of the transformer so that diagrams may be drawn to scale.

Results Required.—

a. Vector diagrams for each of the above performed. Show coil and line currents in the delta connections and coil and line voltages in the wye connections. Explain diagrams.

LAWRENCE, "Principles of Alternating-Current Machinery," p. 272.

H. W. TOBEY, "Relative Merits of Three-phase and One-phase Transformers," *Trans. A.I.E.E.*, 1907, p. 813.

J. S. PECK, "Relative Advantages of One-Phase and Three-Phase Transformers," *Trans. A.I.E.E.*, 1907, p. 817.

39

REGULATION OF AN ALTERNATOR BY THE SYNCHRONOUS-IMPEDANCE METHOD

The synchronous impedance method for determining the regulation of an alternator is valuable in cases where, due to the size of the machine or other reasons, it is impossible to fully load the alternator. The regulation given by this method is always worse than that shown by the actual performance of the machine.

The regulation of an alternator depends upon its armature reaction, its armature leakage reactance and its apparent or effective armature resistance.

The effective resistance of any circuit to an alternating current is always greater than to a direct current due: *a.* to eddy-current losses set up in the conductors of the circuit; *b.* to eddy-current losses set up by the current in any adjacent conducting material; *c.* to hysteresis losses produced by the current in any adjacent iron. The resistance of any circuit to either direct or alternating current is always equal to the total power loss in the circuit caused by the current divided by the square of the current. It is called *effective resistance* in the case of an alternating-current circuit to distinguish it from the resistance of the circuit to direct current. If P_{Cu} is the total power loss in the circuit caused by the current I, the effective resistance is

$$R_e = \frac{P_{Cu}}{I^2}.$$

If the circuit contains no iron the effective resistance is constant and independent of the current, since under this condition the eddy-current loss is all in non-magnetic material and is therefore directly proportional to the square of the current. If the circuit contains iron its effective resistance is neither constant nor independent of the current since in this case neither the eddy-current loss nor the

hysteresis loss produced by the current are proportional to the square of the current. For any given current, however, the effective resistance is still given by the above formula. Effective resistance depends upon the frequency and must, therefore, be determined at the frequency at which it is to be used.

The armature current of an alternator sets up local eddy-current losses in the armature conductors, in the armature teeth and in the pole faces and other adjacent metal. It also causes local hysteresis losses in the armature teeth, in the pole faces and in other adjacent iron. These local losses affect regulation by increasing the apparent armature resistance. Their effect may be taken into account by using the effective armature resistance in all calculations concerning regulation.

There are several ways in which the approximate effective resistance of the armature of an alternator may be found, the most common of which is to measure the power on short circuit, subtract the friction and windage loss, and divide by the number of phases and the phase current squared.

The electromotive force due to the armature reaction flux lags the current by 90°. The back electromotive force due to leakage reactance lags the current by the same angle. These two effects may therefore be combined and the net result represented by a term called synchronous reactance drop which is equal to the leakage reactance drop plus a fictitious reactance drop which replaces the effect of armature reaction.

The alternator vector diagram is shown in Fig. 100 in which all quantities are per phase. V is the phase voltage, I_aR_e is the resistance drop per phase in the armature and is in phase with the armature current, I_a, which in the above diagram is shown lagging. I_aX_s is the electromotive force which is necessary to overcome the electromotive force due to the synchronous reactance X_s. The synchronous reactance electromotive force is 90° behind the current. The electromotive force which must be applied to overcome this is equal and opposite to it, i.e., 180° ahead of it or 90° ahead of the current as shown in Fig. 100. The vector sum of V, I_aR_e and I_aX_s will be the elec-

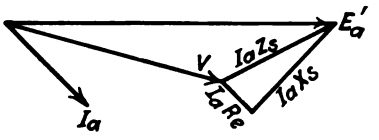


FIG. 100.

tromotive force E_a', which is necessary to produce terminal voltage, V. E_a' is the electromotive force the machine will have if the load is thrown off, i.e., it is the electromotive force at the terminals of one phase at no load. In other words, it is the open-circuit voltage corresponding to the field current which produced the phase voltage V under load.

The vector I_aZ_s, in the diagram is the electromotive force necessary to overcome the synchronous impedance drop of the armature. Since I_aR_e and I_aX_s are at right angles—

$$I_aZ_s=\sqrt{(I_aR_e)^2+(I_aX_s)^2},$$

and

$$Z_s=\sqrt{R_e^2+X_s^2}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

In all alternators, R_e is small compared with Z_s so that Z_s and X_s are sensibly equal and may be so assumed.

If the generator be short-circuited V will become zero and the diagram will collapse into that of Fig. 101.

In this case E_a' is equal numerically to the synchronous impedance drop, I_aZ_s, in the armature. E_a' may be found by keeping the field current and frequency constant and opening the short-circuit. E_a' is the voltage found on open circuit.

$$E_a'=I_aZ_s,$$

$$Z_s=E_a'\div I_a.$$

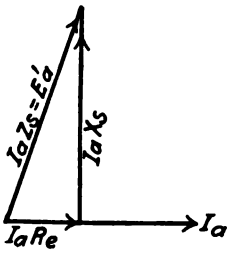


FIG. 101.

If the resistance, R_e, of the armature be known, the synchronous reactance, X_s, may be found from equation (1).

Regulation.—The regulation of an alternator is the percentage increase in voltage produced at the terminals by throwing off full load. If V is the rated full-load voltage and E_a' is the voltage measured when the load is thrown off, the regulation is

$$\frac{E_a'-V}{V}100. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If the rise in voltage is produced by throwing off a full non-inductive load the above expression gives what is called the inherent regulation.

Fig. 102 represents the vector diagram of an alternator with the vectors I_aR_e and I_aX_s exaggerated for the sake of clearness. Drop perpendiculars from the extremities of the vectors V and I_aR_e on the current line, then from the triangles thus formed

$$E_a' = \sqrt{(ob)^2+(bc)^2}$$

$$= \sqrt{(V\cos\theta+I_aR_e)^2+(V\sin\theta+I_aX_s)^2}, \quad . \quad . \quad (3)$$

where θ is the angle of lag of the current behind the terminal voltage, V.

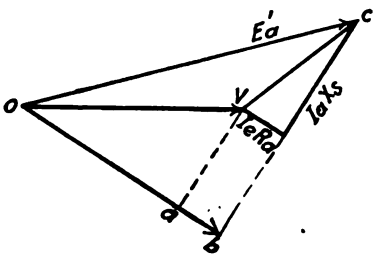


FIG. 102.

If the regulation is required for 0.8 power factor, $\cos\theta=0.8$ and $\sin\theta=0.6$. If the inherent regulation is desired, the angle of lag of the current behind the terminal voltage is zero. Since $\cos\theta=1$ and $\sin\theta=0$, the expression for E_a' in this latter case reduces to

$$E_a' = \sqrt{(V+I_aR_e)^2+(I_aX_s)^2}. \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Having found E_a' the regulation is easily calculated by formula (2).

When determining the synchronous impedance of a machine, it is customary to take the open-circuit characteristic and the short-circuit characteristic instead of using only one excitation as was described on page 229.

The Open-circuit Characteristic.—The open-circuit characteristic or magnetization curve is obtained by running an alternator on open circuit at its rated frequency and measuring its terminal voltage as the field current is increased from zero to a maximum. The descending part of the curve is not necessary in this connection. Open-circuit phase voltages should be plotted as ordinates against field currents as abscissæ.

In taking data for the open-circuit characteristic, the field

current must always be changed in the same sense, i.e., it must not be carried above any desired value and then reduced.

Short-circuit Characteristic.—The short-circuit characteristic of an alternator is taken by short-circuiting the machine through a low resistance ammeter or ammeters if the machine be polyphase and measuring the current in the armature for increasing field currents. Short-circuit phase currents should be plotted as ordinates against field currents as abscissæ.

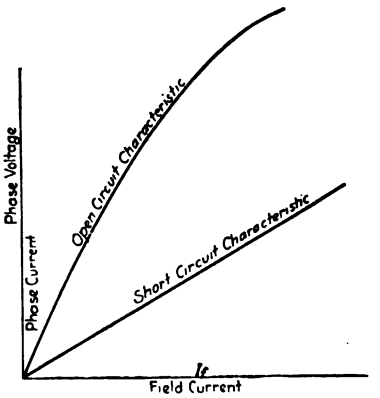


FIG. 103.

The armature current should be carried to a value corresponding to at least 50 per cent. overload. To avoid overheating the alternator the test should be started with very small values of the field current. The field current which will give full-load armature current on short-circuit will vary between 15 per cent. and 30 per cent. of the normal full-load value, depending upon the design of the machine.

If the open-circuit and short-circuit characteristics are plotted, respectively, with phase voltage and phase current, the ratio of the ordinate of the open-circuit characteristic to the ordinate of the short-circuit characteristic for the same field excitation is the synchronous impedance for that excitation. For example: If for any given field current the open-circuit phase voltage and short-circuit phase current are respectively E_a' and I_a, the synchronous impedance is

$$Z_s = E_a'/I_a \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The value of Z_s will vary according to the value of I_f used, decreasing slightly as the field current increases. This is due to the satura-

tion of the field. Normal saturation can never be attained in a short-circuit test. In order that the synchronous impedance used in the calculations shall be for as nearly normal saturation as possible, it should be found for an excitation corresponding to the largest field current it was safe to use in the short-circuit test.

Procedure.—A single-phase or a three-phase △ or Y-connected alternator will be used in this test.

The machine should be driven by a shunt motor, the speed of which can be controlled by a variable rheostat placed in the shunt field.

Open-circuit Run.—The generator connections for this run are shown in Fig. 104. Put several resistance boxes in series with the generator field and then connect it to the d-c. laboratory mains.

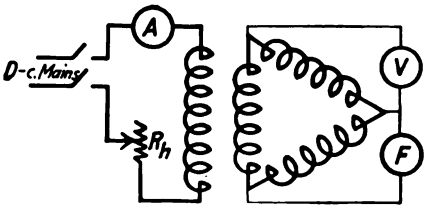


FIG. 104.

An ammeter should be put in circuit. The voltage between all three pairs of armature terminals of a three-phase generator should be the same, so that one voltmeter will be sufficient.

Start the motor and bring the generator up to speed. The proper speed is that which gives rated frequency at the armature terminals and can most readily be obtained by adjusting the motor field so as to drive generator at that frequency. The final speed adjustment should be made very slowly by changing the motor field. After changing the field, wait a few seconds to give the motor time to reach a constant speed before again changing the field. The frequency[1] must be held constant throughout the test. The corresponding speed of the driving motor should be noted for use in the short-circuit run where a frequency meter cannot be used.

With the generator field adjusted for minimum value, read its voltage and field current. Now gradually increase the field current

[1] Note that a frequency meter having only one voltage rating cannot be used here since the voltage is not near rated for all readings.

to a maximum, taking readings of current and voltage for changes corresponding to about 8 per cent. of rated voltage.

Short-circuit Run.—Short-circuit each pair of armature leads through an ammeter having a maximum scale reading equal to not less than 1½ times the rated full-load current of the alternator. This arrangement connects the ammeters in delta, and hence will give the armature phase current directly, provided the alternator is delta-connected. If the alternator is Y-connected, the armature phase current will be the square root of three times the ammeter reading. The field circuit should be connected as before. (See Fig. 105.)

Having made the proper connections start the motor and bring the generator up to its rated speed (adjust driving motor to same speed as before). Put in sufficient resistance in the generator field,

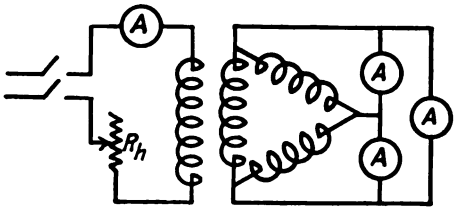


FIG. 105.

so that the field current will not be more than 20 per cent. of the normal value, then close the generator field switch. If the ammeter readings differ by more than 5 per cent. make sure that the connecting leads are of about equal length, and that all contacts are tight in order to avoid excessive resistance in one or more phases.

Read the three ammeters short-circuiting the armature and the ammeter in the field, then increase the field slightly and read again. Proceed in this way until the armature current is equal to at least 1.5 times the full-load rated value, i.e., in the case of a △-machine, (1.5/1.73) I_L where I_L is the rated line current.[1] Readings should be taken for six or seven armature currents between zero and 1.5 times its full-load value. When this is done, open the generator field and shut down the motor.

[1] The armature phase current in a △-connected machine is equal to the line current divided by the $\sqrt{3}$ or 1.73. The phase voltage of the armature is equal to the line voltage. In a Y-connected machine, the armature phase current is the same as the line current, but the phase voltage of the armature is the line voltage divided by 1.73.

The armature resistance per phase must now be measured. This is done by the drop of potential method which has been described earlier. Measure the resistance between each pair of armature leads and take the mean. The proper connections for this are shown in Fig. 106.

A voltmeter with a low-range scale will be needed. Be sure and try the high-range scale before changing to the low.

The resistance found from the voltmeter and ammeter readings will be that of R_1, in parallel with R_2, and R_3 in series.

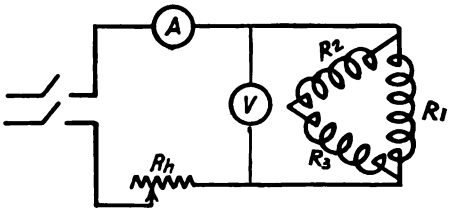


FIG. 106.

This will be equal to

$$R=\frac{1}{\frac{1}{R_1}+\frac{1}{R_2+R_3}}$$

$$=\frac{R_1R_2+R_1R_3}{R_2+R_3+R_1}.$$

If the resistances R_1, R_2, R_3 are all assumed to be equal

$$R=2/3R_1,$$

or

$$R_1=3/2R.$$

If the alternator is Y-connected, the resistance between each pair of armature leads will be equal to twice the resistance per phase, or $R_1=\frac{R}{2}$.

Calculations.—The ratio of the ordinates of the two curves for any given field current will be the synchronous impedance per phase corresponding to that field current. Since, as already stated, the synchronous impedance decreases somewhat as the saturation of the field is approached, the value Z_s used in calculating the regulation of the generator should be taken for as nearly normal conditions of field as possible. The best that generally can be done is

to use the value of Z_s corresponding to the largest field current used in obtaining the short-circuit characteristic.

Calculate this value of synchronous impedance, and from it find the value of the synchronous reactance from equation (1) using for R_e the value of the effective resistance per phase equal to 1.5 times the ohmic resistance per phase.

The inherent regulation can then be found from equations (4) and (2) using the rated voltage per phase of the generator for V and the rated armature phase current for I_a.

Results Required.—

a. Open circuit characteristic (phase voltage against field current).

b. Short-circuit curve (phase current against field current).

c. Curve of synchronous impedance plotted against field current.

d. Calculate regulation for full-load kv-a. at unity power factor and .8 power factor, for both leading current and lagging current using synchronous impedance method.

LAWRENCE, "Principles of Alternating-Current Machinery," p. 90.

CHRISTIE, "Electrical Engineering," p. 261.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. II, p. 138.

L. A. HERDT, "The Determination of Alternator Characteristics," *Trans. A.I.E.E.*, 1902, p. 1093.

B. A. BEHREND, "The Experimental Basis for the Theory of the Regulation of an Alternator," *Trans. A.I.E.E.*, vol. 21, 1903, p. 497.

H. M. HOBART and F. PUNGA, "A Contribution to the Theory of the Regulation of an Alternator," *Trans. A.I.E.E.*, 1904, p. 291.

A. B. FIELD, "The Experimental Determination of the Regulation of Alternators," *Trans. A.I.E.E.*, 1913, p. 783.

T. S. EDEN, "Relative Merits of Y- and Delta-Connection for Alternators," *Trans. A.I.E.E.*, 1914, p. 803.

REGULATION OF AN ALTERNATOR BY THE A. I. E. E. METHOD

The method for determining tne regulation of an alternator which is recommended in the Standardization Rules of the American Institute of Electrical Engineers, is a modification of the regular synchronous-impedance method. One of the chief reasons why the regular synchronous impedance method fails to give satisfactory results, is the low saturation at which the synchronous impedance is obtained. In the regular synchronous-impedance method, the synchronous impedance is obtained from measure-

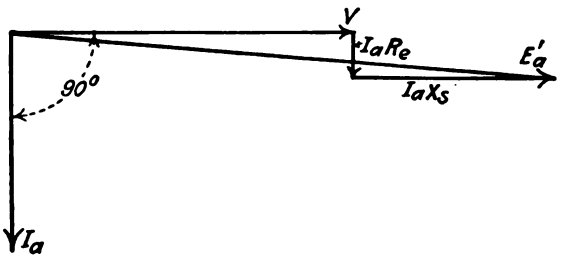


FIG. 107.

ments made with the generator operating short-circuited. Under this condition, the saturation is much lower than under operating conditions and, as a consequence, the value of synchronous impedance which is obtained is much too large for normal operating saturation. This error is largely avoided by the modified synchronous-impedance method as recommended in the Standardization Rules.

The vector diagram of an alternator is shown in Fig. 100 in which all quantities must be per phase, if reference is made to a polyphase machine. If the power factor is zero, the current will lag 90° behind the terminal voltage, V, and Fig. 100 will change to the form shown in Fig. 107.

Under this condition, the resistance drop, I_aR_e, has relatively little effect and $E_a' - V = I_aX_s$ approximately, where V is the phase terminal voltage produced by some excitation I_f with a load of I_a amperes per phase at zero power factor. E_a' is the open-circuit phase voltage corresponding to the excitation I_f.

$$X_s = \frac{E_a' - V}{I_a}.$$

The diagram recommended in the A. I. E. E. Standardization Rules differs somewhat in appearance from the one shown in Fig. 100, but it is essentially the same.

If an open-circuit saturation curve and a load saturation curve at zero power factor [1] are plotted on the same sheet, the vertical distance between the two curves corresponding to any field excitation will be I_aX_s, the synchronous reactance drop, corresponding to the saturation produced by that excitation. An open-circuit saturation curve and a load saturation curve at zero power factor are shown in Fig. 108.

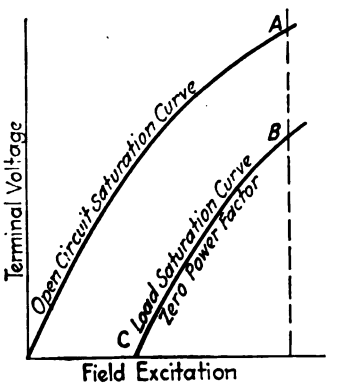


FIG. 108.

$$X_s = \frac{AB(\text{volts})}{I_a}$$

In order to apply this method of getting the synchronous impedance, it is not necessary to have the complete load saturation curve. Two points, such as B and C, Fig. 108, are sufficient. The point B should preferably be taken for about full-load current and normal rated voltage. It is, of course, impossible to get a zero power-factor load, but a load of sufficiently low power factor may easily be obtained by using a synchronous motor for a load and operating this motor without load over-excited. A very low power factor may be obtained in this way. For this experiment, either impedance coils or a synchronous motor will be used to obtain low power factor.

[1] A load saturation curve at zero power factor is a curve showing the relation between field excitation and terminal voltage per phase for a constant armature phase current at zero power factor.

Procedure.—The method of taking the open-circuit curve has been described in the previous experiment.

The connections shown in Fig. 110 may be used for this experiment, using impedances in place of the non-inductive resistances. If it is more convenient, these impedance coils may be connected in Y. The wattmeters are not necessary and may be omitted. After making connections, bring the generator up to rated frequency and adjust the impedances until the generator delivers approximately full-load current at rated voltage. Record the readings of the ammeters and voltmeter, then disconnect the load, and with the generator operating at the same frequency and with the same field excitation record the open-circuit voltage. Then

$$X_s = \frac{E_a' - V}{I_a},$$

where E_a' and V are, respectively, the phase voltages corresponding to the conditions of open circuit and of the zero power-factor load. I_a is the average phase current for the zero power-factor load.

The phase resistance of the armature of the generator should be measured in the way described on page 234. This should be multiplied by a constant to get the effective resistance. This constant may be supplied by an instructor, or determined by the method described in Experiment 43. The method of calculating regulation is described in the previous experiment.

Results Required.—

Regulation for full load current at

a. Unity power factor.

b. 0.8 power factor lagging current.

c. 0.8 power factor leading current.

d. Repeat (*a*), (*b*), and (*c*), using the general method (Lawrence "Alternating Current Machinery," page 87).

"Standard Handbook for Electrical Engineers," (24), 4394.
LAWRENCE, "Principles of Alternating-Current Machinery," p. 104.
PENDER, "Handbook for Electrical Engineers," p. 1341.
DAWES, "Electrical Engineering," vol. II, p. 159.

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REGULATION OF AN ALTERNATOR BY THE MAGNETOMOTIVE FORCE METHOD

In the synchronous impedance method for determining the regulation of an alternator the effect of armature reaction is replaced by an equivalent armature reactance which is added to the real armature reactance, i.e., to the armature leakage reactance. The opposite substitution is made in the magnetomotive force method. In this method an equivalent armature reaction replaces the effect of the real armature leakage reactance. The application of this method involves two things, viz.: 1st. The determination of the amount of field current necessary to generate a voltage equal to that of the reactance drop plus the voltage generated by armature reaction flux. 2d. The vector addition of this field current to that necessary to induce a voltage equal to the terminal voltage plus the I_aR_e drop in the armature.

The resultant of these two field currents is the impressed field and the voltage corresponding to this field on the open-circuit curve is the no-load voltage.

The field current on the short-circuit curve represents the field necessary to equalize the armature reaction flux and in addition to generate a voltage equal to the impedance drop in the machine itself. This field may be assumed to balance the armature reaction and reactance effects. This assumption neglects the effect of armature resistance which is negligible on short-circuit compared with the effects of armature reactance and reaction. The armature reaction being in phase with the current, this field will be 180° from the current.

The vector addition of the I_aR_e drop to V will give a fictitious induced voltage E_a''. The field, R'', corresponding to E_a'' on the magnetization curve is 90° ahead of it.

The value of the current and the angle between the current and V must be known or assumed. R_e being known E_a'' may be determined since I_aR_e is in phase with I_a. The field current R'' corresponding to E_a'' on the magnetization curve may then be found. The field current A' is taken from the short-circuit curve and corresponds to armature phase current, I_a.

F is the vector sum of A' and R'', and the voltage corresponding to F is the open-circuit voltage from which the regulation may be figured as in the synchronous-impedance method.

It must be remembered that both the synchronous impedance and magnetomotive force methods are based on certain assumptions so that the results obtained may be in considerable error. One

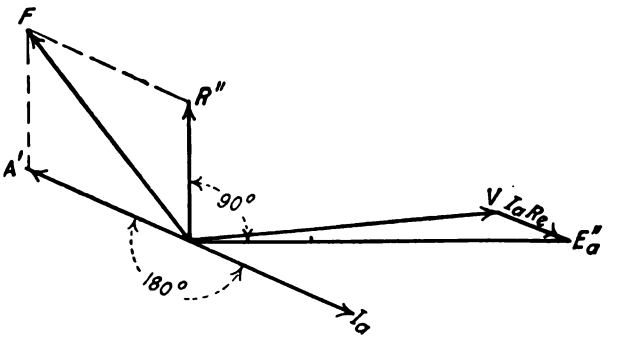


FIG. 109.

method may give better results than the other on one machine and poorer results on another. As a general rule, the magnetomotive force method gives the better results since certain errors due to the low power factor and low saturation at which the measurements for determining A' have to be made tend to cancel, while in the synchronous-impedance method for determining regulation similar errors are additive. The magnetomotive force method is recommended by the American Institute of Electrical Engineers in all cases where the so-called A. I. E. E. or zero power-factor method cannot be used.

Procedure.—The data required is the same as that for determining the regulation by the synchronous impedance method in Experiment 39. See Experiment 39 for the method of calculating regulation.

Results Required.—

Regulation at full-load current for

a. Unity power factor.

b. 0.8 power factor lagging current.

c. 0.8 power factor leading current.

LAWRENCE, "Principles of Alternating-Current Machinery," p. 90.
DAWES, "Electrical Engineering," vol. II, p. 155.
KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. II, p. 138.

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MEASURED EFFICIENCY AND REGULATION OF AN ALTERNATOR

In this experiment the regulation and efficiency of a three-phase alternator will be determined for a non-inductive load by actually applying load. Three non-inductive resistances will be used for the load. A direct-current shunt motor will be used to drive the alternator. The proper connections are shown in Fig. 110.

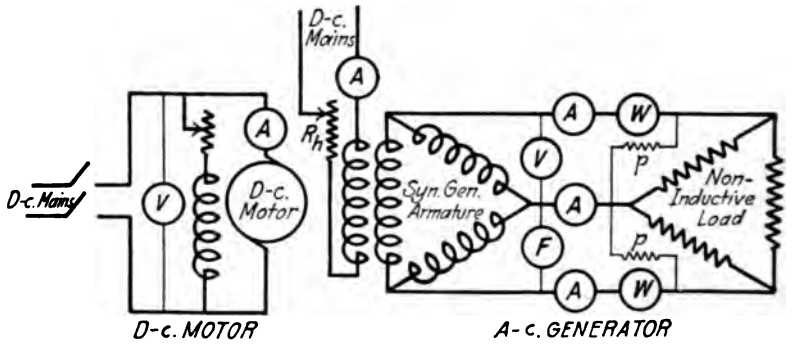


FIG. 110.

Procedure.—Short-circuit all ammeters and wattmeter current coils, and see that the switches connecting the resistance loads to the generator are open. Cut all the resistance out of the motor field, then close the switch connecting the motor to the mains, and bring the motor up to speed by means of its starting rheostat. Now close the generator field and bring the terminal voltage of the generator up to rated value, and then adjust the speed of the motor by means of its field rheostat until the generator runs at its rated frequency. Now readjust voltage to its rated value.

Now gradually load the alternator, at the same time keeping the frequency and voltage of the generator constant, and at approximately their rated values. The load must be kept balanced. Read current, voltage, frequency, power and field current

of the alternator, as well as motor armature current and voltage for each increase in load.

When the ammeters register approximately full-load current, carefully adjust the frequency and voltage of the alternator to exactly their rated values, at the same time holding the generator load constant at its rated value.

Having taken all the readings, remove the load gradually keeping frequency and field current constant. Read line current and voltage. Readjust the generator frequency by means of the rheostat in the motor field to rated value and see that field current of the generator is unchanged. Read the voltage at the terminals of the generator. If this be called E_a', and the voltage when under full load be called V

$$\frac{E_a' - V}{V},$$

will be the regulation for full non-inductive load.

To find the efficiency of the generator, it is necessary to find its input. This can be found by subtracting from the input to the armature of the motor, the stray power and the $I_a^2 R_a$ loss in the motor armature.

The stray power is to be found by the method described in the experiment on stray power (see page 134).

In order to do this, the motor must be shut down and its armature resistance measured at an armature current corresponding to full-load conditions on the generator. Having determined the armature resistance, calculate the induced armature voltage of the motor when driving the generator under full load and also for no load. This will be $V_t - I_a R_a = E_a$, where R_a is the value of the armature resistance found, and I_a is the current in the motor armature when driving the generator under the condition for which E_a is computed.

Disconnect the motor from the generator and start it up idle, with a variable resistance inserted in the armature circuit. Now adjust the armature rheostat and field rheostat of the motor until it runs at the same speed, and has the same induced armature voltage that it had when driving the generator fully loaded. In making this adjustment it will be found convenient to adjust first the armature voltage by means of the armature rheostat and then the speed by means of the field rheostat. When the motor is running idle the armature voltage may be assumed equal to the terminal

voltage. Read and record the speed, armature current, and terminal voltage. Call these latter I_{a_0} and V_{t_0}.

Repeat adjusting the value of E_a corresponding to the no-load condition.

The stray power is $I_{a_0}V_{t_0} - I_{a_0}^2R_a = P_{SP}$.

This is the stray power corresponding to the condition of load on the generator for which $E_a = V_{t_0}$ was taken.

The product of the motor armature current, I_a, by the terminal voltage, V_t, gives the input to the motor armature.

The input to the generator armature under full load including the belt loss is

$$I_aV_t - P_{SP} - I_a^2R_a = P,$$

where I_a and V_t are respectively the current in the motor armature and the voltage at the terminals of the armature, when driving the generator fully loaded.

The loss in the generator field will be $P_f = I_fV_f$.

If the belt loss be counted as one of the losses of the generator, the efficiency of the generator on full non-inductive load will be

$$\eta = \frac{P_1 + P_2}{P + P_f},$$

where P_1 and P_2 are the reading of the two wattmeters measuring the output of the generator and P and P_f are, respectively, the output of the motor and the generator field loss.

The power factor of the load is given by

$$\frac{P_1 + P_2}{(I_1 + I_2 + I_3)\frac{V}{\sqrt{3}}} = \cos\theta,$$

where P_1 and P_2 represent the readings of the two wattmeters, I_1, I_2 and I_3, the readings of the three ammeters, and V the reading of the voltmeter. If the load is balanced, the readings of the voltmeter should be the same between any pair of terminals.

Results Required.—

a. Power factor of load at full-load current.

b. Resistance of motor armature.

c. Stray power of motor corresponding to full-load and no-load conditions of generator.

d. Loss in generator field at full-load.

e. Regulation of generator on full non-inductive load.

f. Curve of terminal voltage versus line current for varying load with constant field. (Start at rated voltage at full load.)

g. A comparison of the measured and calculated regulation, if the previous experiments have been performed.

h. Efficiency curve of generator at constant rated voltage.

i. Curve of generator field current versus line current for constant terminal voltage.

Considerable material on the loading of alternators may be found in *Trans. A.I.E.E.*, 1913, part I.

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EFFICIENCY OF AN ALTERNATOR FROM ITS LOSSES

The losses of an alternator may be divided into two classes which are known as no-load or open-circuit losses and load- or short-circuit losses. The no-load losses minus the field copper loss correspond to the stray-power losses of a direct-current shunt dynamo. The no-load losses are:

a. Friction and windage.

b. Core loss due to the resultant field.

c. Copper loss in the field windings and the field rehostat.

The load losses include all losses which are either directly or indirectly caused by the armature current. These are:

e. Copper loss in the armature winding due to the ohmic resistance.

f. Local eddy-current and hysteresis losses set up in the armature teeth, the pole faces and other metal adjacent to the armature winding by the armature current. These local losses may be from 30 to 50 per cent. as great as the armature copper loss due to the ohmic resistance.

Under load conditions both classes of losses exist but most of the no-load losses are changed in magnitude by the load. If the no-load and load losses are determined for any given load, the efficiency at that load may be calculated.

$$\text{Efficiency} = \frac{\text{Output}}{\text{Output} + \text{No-load Losses} + \text{Load Losses}}.$$

No-load Losses = Open-circuit core loss corresponding to the rated voltage, plus the friction and windage loss, plus the copper loss in the field winding and the field rheostat. This last loss may be found from $I_f^2 R_f$ where R_f is the resistance of the field winding plus the resistance of the field rheostat. It is easier to find the

loss in the field circuit including the field rheostat from $I_f V_f$ where V_f is the rated voltage of the field circuit.

The field current should be calculated by finding the open-circuit voltage of the alternator for the given load by the A. I. E. E. method and then looking up the field current corresponding to this voltage on an open-circuit saturation curve.

The open-circuit core loss depends upon the frequency and flux. The open-circuit core loss plus friction and windage may be determined for any given flux and frequency by measuring the power required to drive the alternator at rated frequency with its armature circuit open and with its field excited. The power required to drive the alternator with both its field and armature circuits open is its friction and windage loss. This loss subtracted from the power required to drive the alternator with its field excited is the open-circuit core loss corresponding to the frequency and field excitation used. This core loss depends upon the flux through the armature and the frequency. The flux is determined by the net excitation, that is, by the resultant excitation produced by the field current and the armature reaction. At no-load the net or resultant excitation is equal to that produced by the field current alone since the armature reaction is zero.

Under load the net or resultant excitation and the impressed excitation due to the field current may be and indeed are usually quite different. Since the induced voltage is also determined by the net excitation and the frequency, the core loss should be found for an induced voltage corresponding to load conditions. At no-load the induced voltage is equal to the terminal voltage. Under load it is equal to the terminal voltage plus the effective resistance and leakage reactance drops. In most cases it is close enough to assume the induced and terminal voltages equal. When a core-loss curve is to be plotted it should be plotted against armature voltage as abscissæ.

Load Losses = Short-circuit losses for the armature current at which the efficiency is desired.

These losses are equal to $3I_a^2R_e$ where I_a is the phase current and R_e is the effective resistance per phase. The load losses are also equal to $3I_a^2R_{oh}$ plus the short-circuit core losses corresponding to the current I_a. R_{oh} is the ohmic resistance per phase.

The load losses may be found approximately by short-circuiting the armature of the alternator and then measuring the power

required to drive it when the excitation is adjusted to give an armature current equal to that for which the losses are required. This power minus the friction and windage loss is the load loss. The load loss minus the armature copper loss caused by the ohmic resistance is the short-circuit core loss. The short-circuit core loss consists principally of eddy-current and hysteresis losses set up in the armature teeth, the pole faces and other adjacent metal by the local flux produced by the armature current. It also includes the eddy-current losses set up in the armature conductors themselves.

The load loss per phase divided by the square of the phase current is the effective resistance per phase.

In many cases the load loss found from short-circuit data is exaggerated due to field distortion and other causes. For this reason the effective resistance found by the method just outlined is often too large.

$$\text{Efficiency} = \frac{\sqrt{3}V_L I_L \cos\theta}{\sqrt{3}V_L I_L \cos\theta + (3I_a^2 R_{oh} + P_{(h+e)s}) + P_{h+e} + P_{f+w} + I_f V_f}$$

$(3I_a^2 R_{oh} + P_{(h+e)s}) = 3I_a^2 R_e$ = short-circuit losses for full-load current.

Procedure.—Take data for plotting the open-circuit saturation curve and the open-circuit core-loss curve from 50 per cent. normal field excitation up to the maximum excitation for which the alternator is built. Determine the friction and windage loss. Also take data for finding the short-circuit or load losses curve from zero to full-load current. Measure the armature ohmic resistance and calculate the ohmic resistance per phase. See previous alternator experiments.

A shunt motor should be used to drive the alternator. In measuring the losses of the alternator it will be sufficiently accurate to assume the stray power of the shunt motor used to drive it to be constant. The stray power should be found for the speed at which the motor must be run to drive generator at rated speed and for a voltage equal to the voltage of the line from which the motor is operated. The input to the armature of this motor minus the armature copper loss, the stray-power loss and the belt loss, if alternator is belt driven, is the input to the alternator.

The belt loss may be found by the use of a light cotton belt having negligible loss.

The belt loss must be determined and subtracted from the out-

put of the motor to get the input to the alternator. All measurements must be made at rated frequency.

The synchronous reactance will be needed in finding the field current. This reactance should be found by the A. I. E. E. method.

Results Required.—

a. A curve of open-circuit core loss for rated frequency plotted against open-circuit voltage as ordinates. This curve should extend from about 50 per cent. normal voltage to the voltage given with the maximum permissible field excitation.

b. Open-circuit magnetization curve for rated frequency for the same range of voltage as curve (*a*).

c. Friction and windage loss for rated frequency.

d. Short-circuit core loss for rated frequency from zero to full-load current.

e. Ohmic and effective resistances per phase.

f. Efficiency curve to full kilovolt-ampere inductive load of 0.9 power factor.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. II, p. 129.

LAWRENCE, "Principles of Alternating-Current Machinery," p. 123.

Considerable material on the losses in alternators may be found in *Trans. A.I.E.E.*, 1913, part I.

44

PARALLEL OPERATION OF ALTERNATORS

The conditions for successful parallel operation of alternators are:

a. That the alternators shall have the same frequency.

b. That the alternators shall be in conjunction with respect to the external circuit.

c. That the alternators shall have the same armature induced voltage.

d. That the wave forms of the alternators shall be the same.

e. That the characteristics of the alternators and their prime-movers shall be the same.

Condition a.—Needs no explanation.

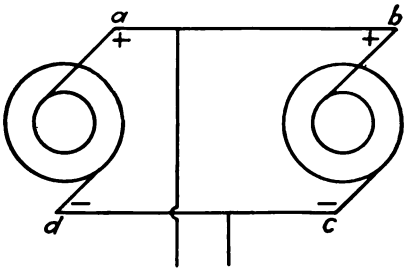


FIG. 111.

Condition b.—The condition of opposition requires that the polarity of any two alternators, when considered with respect to their series circuit, shall be opposite at every instant.

In Fig. 111 the signs indicate the polarity at some particular instant of two alternators which are in parallel. It will be noticed that the two alternators are acting together, i.e., in conjunction, with respect to the external circuit, but they are in opposition when considered in respect to their own or the series circuit.

Opposition on their own circuit is the natural condition of two alternators which are connected in parallel. If they tend to depart from this condition a resultant electromotive force will be produced which will cause a current to flow in the series circuit consisting of the two armatures which will make the alternator which is behind its proper phase position drop a part of its load, and the alternator which is ahead take more load. The effect will be to speed up the first and slow down the second and bring the two back into the proper phase relation.

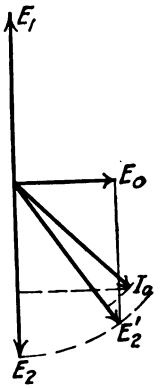


FIG. 112.

This action is readily shown by a vector diagram. Let E_1 and E_2, Fig. 112, be the armature voltages of two alternators which are in exact opposition on their own circuit. Suppose that in some way E_2 gets slightly ahead of its proper position. Let this position be represented by E_2' in Fig. 112. A resultant eelectromotive force E_0 will be produced, acting in the circuit *abcd* in Fig. 111. This electromotive force will cause a current $I_0 = \frac{E_0}{Z_0}$ in the circuit *abcd*, which will lag behind E_0. Z_0 is the resultant impedance of the two generators in series. The power developed by an alternating current is $EI \cos \theta$ where θ is the angle of lag of the current behind the voltage. $I \cos \theta$ is the energy component of the current with respect to the electromotive force and is the projection of the current on the electromotive force vector. If this projection is in phase with the electromotive force, generator action will be developed. If it is opposite in phase to the electromotive force, motor action will be developed.

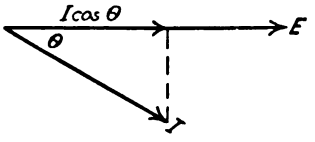


FIG. 113.

It will be noticed that the projection of I_0 on E_2' is in phase with E_2', while the projection on E_1 is in opposite phase to E_1. The current I_0 with respect to alternator No. 2 represents generator action, while with respect to alternator No. 1 it represents motor action. The result is a slowing down of alternator No. 2 and a speeding up of alternator No. 1. This action will continue until the alternators are brought back into opposition. This interchange

of current I_0 is sometimes, though improperly, called the synchronizing current. The true synchronizing current is the component of I_0 which is effective in bringing the alternators into step. Since the natural tendency of two alternators working on the same circuit is to come into opposition, it is impossible except in one case, which is of no practical importance, to operate alternators in series.

Condition c.—If one alternator has a greater armature induced voltage than the other, there will be a resultant voltage, acting in the series circuit consisting of the two alternators. This will cause a current which will lag with respect to the alternator of greater electromotive force and will lead with respect to the other. Since a lagging current in an alternator will cause, by its armature reaction, a decrease in the terminal voltage of the alternator, and a leading current will cause an increase in this voltage, the effect of the interchange of current will be to offset any attempt to increase the voltage of one alternator over that of the other. The interchange of current between the alternators in the above case will be just sufficient to make their terminal voltages equal. Although the alternators will continue to operate with interchange of current, they will operate at a decreased efficiency due to the increase in the copper loss caused by the interchange current.

Condition d.—If this condition is not fulfilled there will be an interchange of current between the machines even though the other conditions are fulfilled.

Condition e.—If the characteristics of the prime-movers, i.e., their change in speed with change in load, are the same, the alternators will divide the load automatically in proportion to their capacities. If, on the other hand, the characteristics of the prime-movers are not the same, the alternators will not divide the load properly.

Prime-movers for alternators must always have drooping speed characteristics, consequently any increase in load will be accompanied by a drop in speed.

The distribution of load between two or more direct-current generators in parallel can be varied by the field excitation. Any attempt to make an alternator, which is operating in parallel with others, deliver more power by merely increasing its field current, will result in failure, since an alternator in parallel with others cannot slow down as a direct-current generator can, and thereby receive more power from its prime-mover. The improper excita-

tion of alternators which are connected in parallel will cause a large interchange of current between them.

The distribution of load between alternators in parallel can only be told by the readings of the wattmeters in each machine circuit. If the load on an alternator is to be increased, it must be done by increasing the driving torque of its prime-mover. If the prime-mover should be an engine, it must be given more steam. It will be necessary to increase the field of the alternator at the same time, but this is merely to make up for the increased armature-impedance drop and has nothing whatever to do with making the machine take load. The load is controlled entirely by the driving torque of the prime-mover.

In order to throw an alternator in parallel with others which are already working, it must first be brought up to speed and the speed of its engine or prime-mover is then varied until the alternator is running in synchronism, i.e., with the same periodicity, and in opposition to the other alternators. Then its voltage is made equal to that of the other alternators and the switch connecting the alternator to the bus bars may then be closed.

To make the alternator take load, the driving torque of its prime-mover is increased, and, to make up for the increase in the armature-impedance drop, the field excitation of the alternator is also increased.

Some form of synchronizing device must be used for telling when the incoming alternator is in opposition to the others. The simplest form of synchronizer, and one which is perfectly satisfactory for small alternators, is an incandescent lamp connected in series with the alternator and bus bars, and across main switch. If high-voltage alternators are to be synchronized, transformers will be required in connection with the lamp.

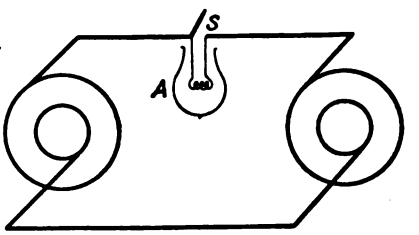


FIG. 114.

If a lamp be placed at *A*, Fig. 114, it will be bright when the alternators are in conjunction on their series circuit. In this case it will receive twice the voltage of either alternator. It will be dark when the alternators are in opposition. If one alternator is run-

ning slightly faster than the other, the lamp will flicker. The alternator which is being synchronized should be connected to the bus bars when the lamp is dark. The speed should first, however, be adjusted so that the lamp requires several seconds in going from bright to dark.[1]

When large alternators are to be synchronized, some form of synchronizer more accurate than a lamp should be used.

It is well to throw the incoming alternator in parallel when it is running fast rather than slow.

If three-phase alternators are to be synchronized, lamps will be required for each phase. These should all be dark at the same

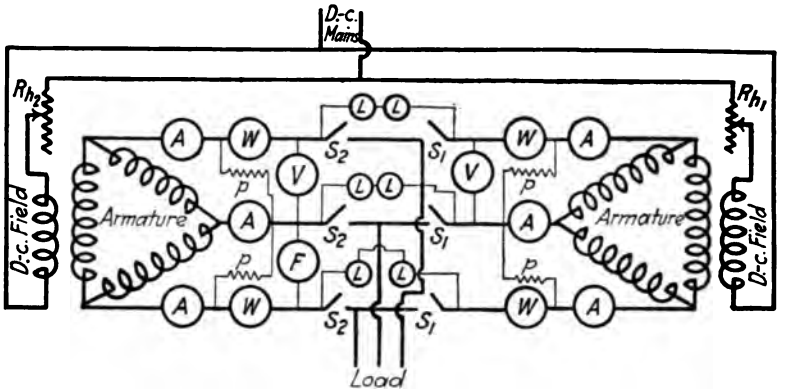


FIG. 115.

time. If they are not, it shows that like phases are not connected together.

Two similar, three-phase alternators, driven by similar direct-current shunt motors will be used in this experiment.

The proper connections for the alternators are shown in Fig. 115.

Lamps of the proper voltage will be used in each phase for synchronizing lamps. The maximum voltage on these lamps will be the line voltage multiplied by $\frac{2}{\sqrt{3}}$.

Procedure.—Connect the alternators as shown in Fig. 115, using two polyphase wattmeters in place of the four wattmeters shown.

[1] If transformers are used in connection with the synchronizing lamp, it is possible, by reversing the connections of the secondaries of one of the transformers, to have the lamp show bright when the generator should be thrown in.

With all switches used in connection with the alternators open, start the shunt motors and bring the alternators up to speed. Close the alternator fields and adjust their terminal voltages to the rated value. Adjust the speed of the alternators by means of the rheostats in the fields of the motors until the alternators run at rated frequency.

Now close the small switch on the synchronizing lamps, and slowly vary the speed of one of the alternators by moving the rheostat in the field of the shunt motor which drives it one notch at a time until four or five seconds are required for the synchronizing lamps to go from bright to dark. Close S_1 and see that the voltage of each alternator is the same, then when the lamps are dark close S_2.

The alternators will now be working in parallel but should be delivering no load. If the voltage and speed have been properly adjusted, there should be no interchange of current between the generators and the ammeters should read zero.

Now load the alternators to what corresponds to about the full load of one. The load should be kept balanced by keeping the currents in the three phases, as indicated by the ammeters, equal.

Take the readings of the wattmeters and the ammeters after each change in load.

If the power output of one alternator increases faster than in the other, it shows that the speed characteristics of the driving motors are not exactly the same, or it may possibly show belt slip. If, on the other hand, the power outputs increase together but the current in one alternator increases faster than in the other, it shows that the characteristics of the alternators are not the same. If the two motors and the two alternators are the same, their characteristics should be nearly identical and the watts and amperes in each machine circuit ought to increase at nearly the same rate. The speed characteristics of the motors may, however, be changed considerably by a slight movement of their brushes.

If, when the total load on the system has been adjusted to what corresponds to about the full load for one alternator, the loads on the two alternators as indicated by the wattmeters, are not the same, make them so by slowly increasing the driving torque of the motor connected to the alternator delivering the

least power. A decrease in the motor field will increase its torque.

Now adjust the voltage of the system to its rated value by slowly increasing the field of both alternators in such a way as to keep the ammeter readings in each machine circuit the same.

When this has been done try the effect of an attempt to shift the load from one alternator to the other by increasing the field current of one alternator. Note the readings of the wattmeters, ammeters and voltmeters.

Adjust the field of the alternator until the ammeters in the two machine circuits again read alike and the voltage of the system is approximately normal, then take one alternator out of service by slowly decreasing the driving torque of its motor at the same time weakening the field of the alternator which is being taken out and increasing the field of the other in such a way as to keep the potential of the system constant and the currents in each alternator approximately a minimum for the power it is delivering. When the wattmeters and ammeters of the alternator which is being taken out read zero, open the switch connected to the bus bars.

Try synchronizing the alternator and again putting it back into service and making it take all the load.

If, when an alternator is being taken out of service, the driving torque of its prime-mover is reduced below that value which makes the readings of the wattmeters in its circuit zero, the alternator will act as a synchronous motor and will deliver power to its prime-mover.

Results Required.

a. Curves of generator output and generator current for each machine, plotted against its own field current for conditions outlined in following procedure. Put all these four curves on the same sheet. Load up to one-half load on each machine and adjust so that there is no interchange current. Then, keeping the line voltage and frequency constant, vary the fields of the two generators over a safe range, i.e., increase one field and decrease the other until each generator is carrying $1\frac{1}{4}$ rated current. Then reverse the process until the same conditions are obtained.

b. Curves of generator output and generator current of each

machine plotted against the field current of its driving motor. Make the preliminary adjustments as in the preceding run and then vary the driving torque of the two machines, keeping the frequency constant.

c. Vector diagrams showing the conditions when a large interchange current is flowing. Take data from (*a*).

d. Heating due to the interchange current for the above condition.

e. What would be the effect on the distribution of load if an additional resistance were inserted in the armature circuit of each driving motor?

f. Two unlike synchronous generators are to be operated in parallel on a non-inductive load. What field currents should the generators have for best operations at $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$ full and $1\frac{1}{4}$ load, the load being divided in proportion to the generator ratings. How could the driving motor characteristics be changed so as to give proper division of load at all times?

DAWES, "Electrical Engineering," vol. II, p. 163.

CHRISTIE, "Electrical Engineering," p. 281.

LAWRENCE, "Principles of Alternating-Current Machinery," p. 341.

G. I. RHODES, "Parallel Operation of Three-Phase Generators with their Neutrals Interconnected," *Trans. A.I.E.E.*, 1910, p. 765.

45

SYNCHRONOUS MOTOR

A direct-current motor can never run with an armature voltage which is greater than, or even as great as the voltage impressed on its terminals. A synchronous motor, on the other hand, may be operated even though its armature voltage is considerably greater than the voltage at its terminals. The possibility of running under this condition, or over-excited as it is called, is due to the phase displacement of the current with respect to the electromotive force.

A synchronous motor must run, up to its limit of output, in synchronism with the generator. Its speed therefore is fixed by the speed of the generator and will be equal to the frequency of the circuit from which the motor is run multiplied by 60 and divided by the number of pairs of poles on the motor.

The power factor of a synchronous motor operating at a fixed terminal voltage is determined by its excitation. The excitation which makes its power factor unity is called the normal excitation. If a synchronous motor is over-excited, it will take a leading current from the line and will act like a capacity or condenser load. If this motor is under-excited it will take a lagging current from the line and will be equivalent to an inductive load.

Synchronous motors which are used for power purposes are generally slightly over-excited at no-load as this increases their stability under load. Under this condition the power factor will rise to unity as the motor is loaded, reach unity and then fall again.

The load at which the power factor becomes unity will depend upon the impressed voltage, the frequency and the motor field current. The field current for unity power factor at any load may be found by varying the field current until the armature current is a minimum.

Curves showing the variation of armature current with field current for different constant inputs are called, from their shape,

the V-curves. These curves may be plotted with line currents if more desirable. A V-curve of a synchronous motor is shown in Fig. 116.

The lowest point of this curve gives the field current for unity power factor for the load for which the V-curve is drawn. Field currents less than this will cause the motor to take a lagging current from the line while greater field currents will cause the motor to take a leading current. The possibility of making a synchronous motor take either a lagging or leading current renders a motor of this type particularly valuable in connection with power transmission.

Synchronous motors may be used over-excited to balance an inductive load on the line and produce unity power factor. They

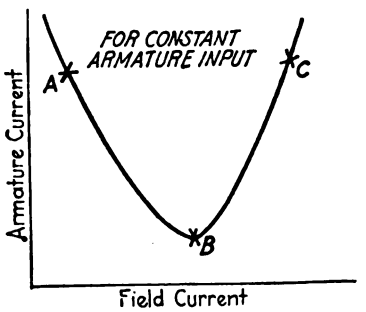


FIG. 116.

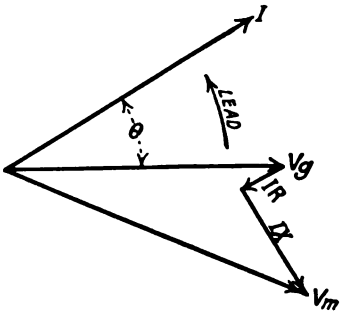


FIG. 117.

may also be used over-excited at the end of a transmission line to regulate the voltage. Synchronous motors cannot, however, be used for this latter purpose unless there is reactance in the line between the motor and the generator. With line reactance it is perfectly possible by over-exciting the motor to have the potential at the motor end of the line greater than at the generator end. The possibility of producing a rise in voltage by a leading current is shown by Fig. 117.

V_g represents the voltage at the generator end of the line. I is the line current leading the generator voltage by an angle θ. The voltage of the motor end will be the generator voltage minus, vectorially, the resistance and reactance drops in the line.

IR represents the resistance drop subtracted from V_g; IX represents the reactive drop of the line subtracted. V_m is then the voltage at the motor which, as will be noticed, is greater than the

generator voltage V_g. The amount by which this is greater will be dependent upon the values of R and X, i.e., the resistance and reactance respectively of the line, the angle of lead, θ, and the line current.

A synchronous motor, as such, is not self-starting. Some kind of starting device must always be used for single-phase motors. These latter are seldom used, but when they are, they are generally started by bringing them up to speed with their direct-current fields on, by a separate motor, then, adjusting their voltage, phasing or synchronizing them, and throwing them on the line as if they were generators. After a motor of this type has been connected to the line the auxiliary starting motor may be shut down.

Polyphase motors may be started without load as induction motors. If a polyphase synchronous motor be connected to the mains with its direct-current field open, it will start and come up to speed as an induction motor, the amortisseur or damping winding in the pole faces acting like the squirrel-cage winding on the rotor of an induction motor. The starting torque will also be somewhat increased by eddy-current and hysteresis losses produced in the pole faces by the revolving magnetic field set up by the polyphase currents in the stator windings. If, when the motor is up to speed, its direct-current field be gradually thrown in, the motor will come into step and run as a synchronous motor.

If a motor of any size is thrown directly on the line, as indicated above, a very heavy lagging current will flow which will seriously disturb the voltage of the mains. To avoid this, polyphase synchronous motors, except in the smaller sizes, are started with reduced voltage from a compensator. The voltage induced in the direct-current field at starting may be very great. Hence to avoid danger of puncturing the field, the field circuit should be broken in a number of different places in order that the potential induced in any one section shall not be great enough to cause damage. The necessity for sectionalizing the field may be avoided by insulating the field coils for high voltage.

Use a three-phase synchronous motor with a compensator for starting.

Procedure.—The following procedure assumes the motor to be started by a compensator and loaded by some form of brake. In case there is no brake provided and it is necesary to use a direct-

current generator for load the starting procedure is the same if a compensator is provided. If none is provided the set may be started from the direct-current side and synchronized. See Expt. 46. The output of the generator may be absorbed by resistances or pumped back into the direct-current mains. Connect the motor according to Fig. 118, using the two-wattmeter method for measuring power. Fig. 118 shows the proper connections in case a direct-current generator is used as load.

When the connections have been properly made, short-circuit the wattmeters and ammeters, loosen the brake if one is used, and close S_1 connecting the compensator to the mains and bring the motor up to speed by means of the compensator, being careful not to advance the compensator too rapidly

When the motor is up to speed. which ought not to take over

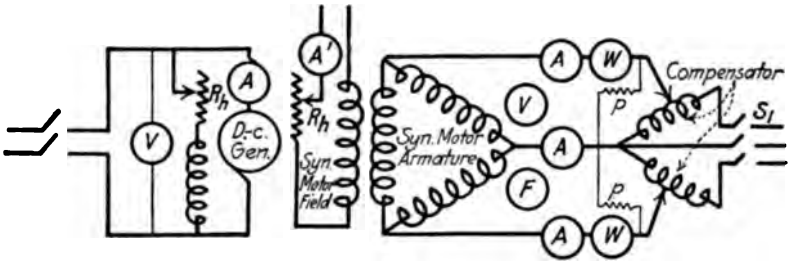


FIG. 118.

a few seconds, close the field switch and then apply full voltage to the stator of the motor. Then adjust the current in its field to make the line current a minimum.

Load the motor until it takes three-fourths its rated current, then slowly change the motor field current until the line current is a minimum. Record this value of the field current. This is the field excitation for the load test. The power factor of the system will now be unity, and consequently the two wattmeters should read alike.

Throw the load off of the motor and read all the instruments including the spring balance if a brake is used. Also record the frequency of the circuit. The speed of the motor in revolutions per minute may be found by dividing the frequency of the circuit multiplied by 60 by the number of pairs of poles on the motor.

Increase the load on the motor to about one and one-fourth times its rated load in about eight steps recording the readings of

all the instruments at each step. The field excitation must be kept constant during the entire run. If there is any means of controlling it, the frequency of the circuit from which the motor is operated should also be kept constant. If the motor should reach its maximum load during the test and break down, i.e., fall out of synchronism, immediately open the main switch.

It is next desired to obtain data for the curves shown in Fig. 119.

The curves shown in the order in which they are numbered are, respectively, the V-curve, the curve showing the voltage rise due to reactance, the curve showing the voltage rise with neither reactance nor resistance in circuit, and the curve showing the rise with resistance.

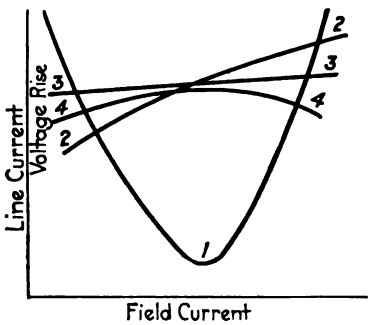


FIG. 119.

It is important to notice that no rise in voltage can be obtained unless there is reactance in series with the motor. It should also be noticed that little change in voltage can be produced with the reactance in circuit unless the motor is over- or under-excited.

A three-phase or three single-phase reactances and three similar resistances will be required. These will be placed in series with the motor and must, therefore, be capable of carrying the line current without dangerous heating. Connect the motor according to Fig. 118.

V-curves.—This should be taken with neither resistance nor reactance in series with the motor and with no-load on motor. Bring the motor up to speed, according to the directions already given, and adjust its field excitation for minimum armature current. Record the readings of all instruments. Now increase the excitation until the motor takes about one and one-quarter full-load current from the mains and again record the indications of all instruments. Decrease the field in about ten steps until the current taken by the motor has passed through a minimum and has again risen to about one and one-quarter full-load current. Take readings of field current and line current at each step. Repeat for $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ rated armature input.

Curves of Voltage Rise with No-load on Motor.—With neither resistance nor reactance.—Data for this can be obtained while making the test for the no-load V-curve by recording the readings of the two voltmeters, one on the mains and one at the motor terminals. Since there is neither resistance nor reactance in the line between these two instruments they should both read alike. Vary the field current from a minimum to a maximum and read field current and terminal voltage. Any slight variation in the voltage is due to the line drop between the switchboard and the source of power.

Curve with Resistance.—Insert the three non-inductive resistances, one in each line between the mains and the motor and take readings of all instruments as the line current is varied from one and one-quarter full-load current leading (corresponding to over-excitation) to one and one-quarter full-load current lagging (corresponding to under-excitation). This change in line current is obtained by varying the field excitation over the same range as was used for the V-curve.

Curve with Reactance.—Replace the resistances by the reactance and then proceed as in the previous run.

Results Required.—

Calculate and plot the following curves:

a. Power-factor and output.

b. Efficiency and output.

c. Torque and output.

d. Indicate on the plot the average speed found during the test.

e V-curves for zero output, $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{3}{4}$ rated armature input.

f. Compounding curves for unity power factor and 0.8 power factor for both leading and lagging current. Construct from V-curves.

g. Curve of motor voltage against field current for neither resistance nor reactance in series with the motor.

h. Repeat (*g*) with resistance in series.

i. Repeat (*g*) with reactance in series.

j. If a three-phase induction motor taking 5 kw. at 0.8 power factor is operated on the same circuit as the synchronous motor tested, find the field current of the synchronous motor which will

make the power factor of the line unity when the synchronous motor takes 5 kw. from the mains. Neglect the effect of resistance and reactance in the mains between machines.

k. Determine the synchronous reactance of the motor by running it over-excited and then under-excited and take mean of the two results.

l. With the machine running at no-load as a motor, take data for the magnetization curve.

m. Determine effective resistance by the retardation method.

n. From the above data, using synchronous impedance method, plot motor armature current versus motor field current?

(1) With no load on motor.

(2) With one-third rated input to motor.

(3) With two-thirds rated input to motor.

o. If in parallel with the motor, there is a load which varies from zero to 12 kv.-a. at 0.8 power factor and the motor is operating without load, what will be the relation between motor field current and load if 230 volts is to be maintained at the motor? The motor is at the end of a transmission line of 0.5 ohm resistance and 1 ohm reactance.

p. How does a decrease of 10 per cent. of the line voltage affect the efficiency of a synchronous motor?

q. How does the torque for rated armature current vary with the voltage? (Power factor is to be held as near to unity as possible.) Plot curve.

r. What conditions may exist which will make unity power factor unattainable.

s. Calculate the free period of a synchronous motor when operating at full non-inductive load, rated voltage and frequency. The moment of inertia should be determined by a retardation run. Check results by means of stroboscope.

HUDSON, "Engineering Electricity," chap. XI.

LAWRENCE, "Principles of Alternating-Current Machinery," p. 297.

CHRISTIE, "Electrical Engineering," p. 271.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. II, p. 120.

E. S. HENNINGSEN, "Synchronous Motors for Ship Propulsion," *Trans. A.I.E.E.*, 1921, p. 1309.

GRAY, "Principles and Practice of Electrical Engineering," 2nd Ed., chap. XXXIII.

46

SYNCHRONOUS MOTOR AND GENERATOR

The synchronous generator, when operating in parallel with other generators, will be converted into a synchronous motor if the torque exerted upon it by the prime-mover is reversed in direction; that is, if the speed of the prime-mover tends to become less than that of the generator, the synchronous generator will become a synchronous motor and drive its prime-mover. Hence, if the prime-mover is a d-c. shunt motor, the synchronous machine may be loaded either as a generator, by decreasing the field of the d-c. machine, or as a synchronous motor by increasing the field of the d-c. machine.

The power factor at which a synchronous motor operates is determined by its excitation. An over-excited synchronous motor operates with a leading current, while under-excitation causes the current to lag. Conversely, when a synchronous generator is operating in parallel with other generators, under-excitation produces leading current and over-excitation lagging current. For any definite load on a synchronous motor (motor initially operating at leading current), the current will decrease as the excitation is decreased until a minimum is reached after which the current will rise again. This point of minimum current corresponds to unity power factor. Fig. 116 shows how the synchronous motor current varies with excitation.

In this test a d-c. shunt motor drives a synchronous machine, either direct connected or belted.

Procedure.—Connect the apparatus as in Fig. 120. The motor is connected as a shunt motor. The field of the synchronous machine is connected across a d-c. line of proper voltage, usually 115 volts. The synchronous motor is connected to the three-phase laboratory mains through switch S_m, which must not be closed, until the synchronous machine runs in synchronism with the

mains. In parallel with each blade of S_m is a pair of synchronizing lamps in series.

Bring the synchronous motor up to speed by means of the direct-current motor, then excite its field. The synchronous motor will now be operating as a generator and will develop voltage across its terminals. Adjust its frequency to approximately that of the mains from which it is to operate, by means of the rheostat in the field of the direct-current motor. Synchronous speed is given by $\frac{60f}{p/2}$ where f and p are, respectively, the frequency of the mains and the number of poles on the motor. Adjust the voltage of the synchronous motor to approximately that of the mains, then close the switch, putting the synchronizing lamps in circuit.

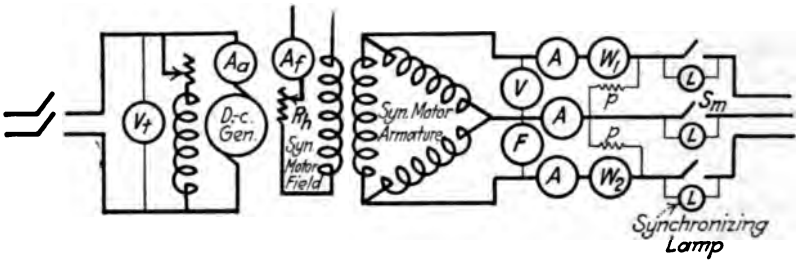


FIG. 120.

The voltage on each pair of synchronizing lamps is equal to the vector sum of the voltage of one phase of the mains and one phase of the synchronous motor. For exact synchronism, these voltages should be exactly opposite when considered with respect to the series circuit containing the lamps. Therefore, if the voltages are equal, at synchronism their vector sum will be zero and the synchronizing lamps will be dark. If the two voltages are not opposite, in other words if the motor is not in synchronism with the mains, their vector sum will not be zero and the lamps will be lighted. The maximum voltage on the synchronizing lamps will occur when the motor is out of phase from synchronism by 180°. This maximum voltage is $\frac{2}{\sqrt{3}} = 1.15$ times the voltage of the mains. If the synchronizing lamps are not all dark at the same instant it indicates that corresponding phases of the motor and mains are not connected together. If this occurs reverse any two of the three-phase lines. Be sure that each switch blade has a

set of lamps connected across it, otherwise the test is of no value. If the frequency of the mains is different from that of the generator the lamps will flicker at a rate proportional to this difference. If the period of flickering is fairly long, the switch S_m connecting the machine to the line may be closed when the lamps are dark for the voltages are then in phase. But if the lamps flicker too rapidly the frequency of the generator must be altered by varying the field of its driving motor until the period of flickering is long enough to permit the closing of the switch. The voltage of the synchronous generator must be made equal to the voltage of the mains before the switch is closed. When the switch is closed the generator is in parallel with the mains and the synchronizing lamp switch should be opened.

Increase the field of the d-c. motor. When its armature ammeter reverses the d-c. machine has become a generator and is being driven by the synchronous motor. Note the effect this has on the speed of the synchronous machine. Increase the d-c. motor field current until the wattmeters indicate one-half load and then adjust the field current of the synchronous machine for unity power factor (a-c. current a minimum or watts $=\sqrt{3}VI$ or $P_1=P_2$) and read all meters. This corresponds to the point B in the V-curve of Fig. 116. With the synchronous motor carrying one-half load, increase its field current until the line current is at rated value, and read meters. This corresponds to point C. Now decrease synchronous motor field until line current passes its minimum and again reaches rated value, then take readings. This corresponds to point A.

Readjust field of synchronous machine for unity power factor and then decrease field of d-c. machine. When its armature ammeter reverses, the machine has become a motor again and the synchronous machine has become a generator. Continue decreasing the field until synchronous generator delivers rated load as shown by the wattmeters. Then adjust field of synchronous machine until current is a minimum, noting the effect of varying excitation on load. Read all meters, then open the a-c. line switch. The synchronous machine whose speed has been dependent upon the frequency of the mains, will now run at a speed determined by the d-c. motor excitation. Hence, this must be adjusted to bring a-c. generator to rated speed and frequency again, or to the frequency it had just before the main switch was opened; when

this is done read the a-c. voltage. This last set of readings is used in calculating voltage regulation.

The efficiency of the synchronous machine when operating at full unity power factor load as a generator is:

$$\eta = \frac{\text{Output}}{\text{Input}} = \frac{P_1 + P_2}{V_t I_a - I_a^2 R_a - P_{SP} - P_b + V_f I_f},$$

where P_1, P_2, V_t, I_a and I_f are respectively the readings of instruments W_1, W_2, V_t, A_a and A_f when the synchronous generator delivers rated output with minimum line current. R_a, P_{SP}, P_b and V_f are respectively the d-c. motor armature resistance, the d-c. motor stray-power at rated synchronous generator speed, the belt loss and the rated d-c. field voltage of the synchronous machine.

The regulation at full unity power-factor load is:

Regulation $= \frac{E_a - V}{V}$ where V is the terminal voltage when the alternator is delivering full load at unity power factor, and E_a is the terminal voltage of the alternator after the load has been removed and the frequency adjusted to its previous value under load.

Results Required.—

a. Efficiency of synchronous generator at full unity power-factor load.

b. Voltage regulation of synchronous generator.

c. Tabulate readings taken on synchronous motor and explain their significance.

d. How does varying the field excitation of a synchronous motor or generator which is in parallel with others affect the load it takes?

e. How does varying the field excitation of the d-c. driving motor affect the speed of a synchronous motor or generator which is operating in parallel with other generators?

f. State the necessary conditions for placing alternators in parallel.

See Experiments 42, 44 and 45.

47

SYNCHRONOUS CONVERTER

It is frequently necessary to transform alternating current to direct current and vice versa. Such a transformation may be accomplished by a motor-generator set, consisting of a direct-current generator coupled mechanically to either a synchronous motor or an induction motor, or by a synchronous or rotary converter. The motor generator and rotary converter each possess certain inherent advantages and disadvantages.

A synchronous converter is essentially a direct-current shunt or compound generator with taps brought out from the armature to slip rings, the number of these taps depending upon the number of phases. Copper damping bridges are attached to the poles to prevent hunting.

Since there is but a single winding on the armature of a synchronous converter, any conductor in this winding must carry at each instant the resultant of the motor and generator currents. Although the heating in all parts of the armature due to this resultant current will not be the same, the total heating due to the resultant of the motor and generator currents will be less, except in the case of the single-phase machine, than that which would be caused by either the direct or the alternating current alone. Consequently, the output of any but a single-phase synchronous converter will be considerably greater than the output of the same converter, used as a simple motor or generator.

The theoretical rating at unity power factor of a synchronous converter as compared with its rating as a direct-current generator is: single-phase, 0.85; three-phase, 1.32; four-phase, 1.62; six-phase, 1.92. These values are based on an assumed efficiency of 100 per cent. and a sine wave of current. The total losses in a synchronous converter will be somewhat less than half of the total

losses in the two machines required for a motor-generator set of equal output.

Since the armature of a converter carries the difference between the alternating and the direct currents, the armature reaction of a converter will be small, and for this reason, no change in brush position will be required with change of load.

The ratio of transformation of a synchronous converter with a fixed brush position is fixed, except in so far as it is influenced by wave form. It depends merely upon the number of slip rings or phases. The ratio of terminal voltages will, of course, differ slightly from the true ratio of transformation on account of the resistance and reactance drops in the armature winding. Changing the field excitation will not affect the ratio of transformation.

The ratios of transformation of converters with different numbers of phases are:

Single-phase	0.707
Three-phase	0.612
Four-phase	0.500
Six-phase	0.354

These ratios are the ratios of the alternating to the direct voltage.

If a synchronous converter is running from the alternating-current side, an increase in the excitation will not affect the speed, but will cause the synchronous converter to take leading current from the line. If the line contains reactance, an increase in the voltage impressed on the rotary will be produced and, as the result of this, the direct-current voltage will rise. (See page 262, under "Synchronous Motor.") Reactance is often artificially placed in a line, in order to obtain control of the voltage on the direct-current side of a converter. If more than a moderate variation in voltage is required, i.e., over about 10 per cent., some form of potential regulator must be used between the rotary and its transformers.

Synchronous converters are seldom operated from the direct-current side, or inverted, as it is called. When so operated, some device for limiting the speed must be used, since an inductive load will produce a demagnetizing effect on the field, and cause the rotary to speed up. A large lagging current or a short-circuit will cause an inverted converter to race, and, if its speed is not limited automatically, it may speed up to the bursting point.

Alternating current is, as a rule, transmitted at high voltage. Direct-current voltages, on the other hand, seldom exceed 700. This usually necessitates the use of transformers between the line and a synchronous converter in order to obtain the proper direct-current voltage. These transformers somewhat increase the cost of the synchronous converter set, and they slightly lower its efficiency. These transformers are frequently designed to have considerable reactance so that voltage variation may be obtained without resorting to separate reactance units.

Starting Synchronous Converters.—A synchronous converter may be started in three different ways. 1st, as a direct-current motor from the direct-current side. In this case it has to be synchronized. 2d, by an auxiliary motor on the shaft. An induction motor is generally used for this purpose. In this case the machine must also be synchronized. 3d, as an induction-motor with its direct-current field left open until the converter is up to speed. In this last case no synchronizing is necessary but unless the field is separately excited there is no way of predetermining the polarity of the converter before the field is closed. The polarity of a self-excited rotary depends upon the position of the armature with respect to the poles at the instant the field circuit is closed. When a converter is started as an induction motor there will be a high voltage induced in its field winding by the transformer action which exists between it and the armature. This transformer action will cease as soon as synchronous speed has been reached. Danger to the field winding is avoided by opening it in several places so as to diminish the total voltage acting on the insulation of any one section.

Procedure.—This test will be performed on a three-phase or six-phase synchronous converter. The rating of the converter assigned should be obtained from its name plate. In order to get the correct voltage for the alternating-current side of the converter transformers will be required. Either three single-phase transformers connected for three phase, two T-connected transformers, or one three-phase transformer may be used. The method of connecting the transformers should be indicated in the assignment. The converter will be started by means of a compensator placed between the transformers and the converter.

In this test, consider the transformers and synchronous converter as a unit, putting the alternating-current instruments out-

side of the transformers in order to measure the total input to the system.

The diagram of connections is shown in Fig. 121.

The transformers shown in Fig. 121 are T-connected. This does not, however, mean that T-connected transformers will necessarily be used.

Make the connections according to Fig. 121 if a three-phase synchronous converter is used. See that the compensator handle is in the position marked "off," then open the sectionalized field switch (not shown in diagram). Now close the main line switch and swing the handle of the compensator into the first marked position. If the converter starts in the wrong direction, i.e., against the alternating-current brushes, open the switch and inter-

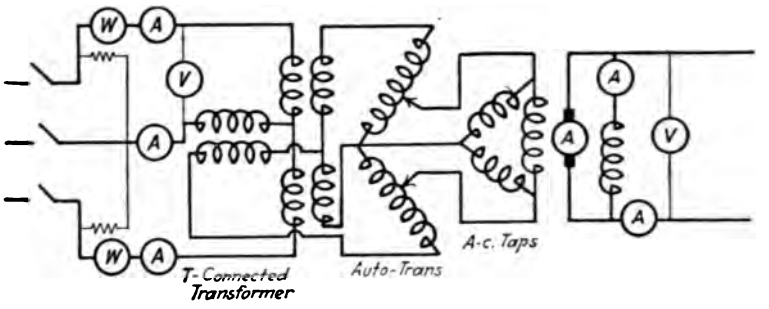


FIG. 121.

change any two of the three alternating-current leads at the line. If the converter starts in the proper direction, put the handle of the compensator in successive positions as the machine speeds up. When the next to the last position is reached wait until the synchronous converter is running at or near synchronous speed, then close the field switch and swing the handle of the compensator quickly into the running position. In this position the compensator is entirely cut out. If the synchronous converter slows down as soon as the field is closed, the main switch should be opened immediately. If the converter fails to build up when the field is closed and sparks badly at the commutator, the field connections are probably reversed or the direct-current brushes are not in their correct position.

As soon as the field circuit has been closed, and the compensator has been put in the running position, partially remove the

short-circuit from one of the alternating-current ammeters and adjust the field current of the converter, so as to make the alternating current ammeters read approximately a minimum. Now apply about three-quarters load. Readjust the field to produce a minimum line current for this load.

Throw off the load and record the readings of all instruments. Add about one-eighth load and again read the instruments. The frequency should also be recorded. Proceed in this way until about one and one-fourth full load has been reached.

Now reduce the load to about three-quarters and note the rise in the direct-current voltage, produced by an increase in the field excitation, also note the effect of this on the power factor. The change in the voltage, which is produced by altering the field excitation, is not due to a change in the ratio of transformation of the converter, but is caused principally by the rise in voltage through the transformers. The rise in voltage through the transformers is due to the leading current produced by the over-excitation of the converter. If the transformers and rotary were without reactance, no appreciable change of voltage could be produced by field excitation. Under-excitation will cause a lagging current and a fall of voltage.

Results Required.—

a. Efficiency curve of the synchronous converter against kw. output, when operating with normal field current, i.e., the field current which makes the power factor at the synchronous converter unity, when it is taking three-quarter rated current from the transformer.

b. Efficiency curve of the system for the above condition.

c. Curve of power factor and output.

d. Curve of direct-current voltage and output.

e. Curve of alternating-current voltage and output.

f. Synchronous converter stray power at normal field.

g. Synchronous converter equivalent resistance. Determine from measured ohmic resistance and equivalent heating formula in " Alternating Current Machinery," p. 409, by R. R. Lawrence.

h. Transformer losses for full-load on the synchronous converter. Determine copper losses from d-c. resistance measurements.

i. Full-load efficiency of synchronous converter from no-load measurements.

j. Full-load efficiency of system from no-load measurements.

k. Assuming depreciation, insurance, interest and taxes at 18 per cent. and power at 4 cents a kilowatt hour, what will be the saving at full-load effected by the use of a synchronous converter set instead of a motor generator set? The motor generator set consists of a direct-current compound generator driven by an induction motor, and their efficiencies may be assumed as 83 and 85 per cent. respectively. The cost of the rotary converter and transformers as well as the cost of a motor generator set of the same capacity should be supplied by the instructor. Assume sets to operate at full load 50 per cent. of the time for the year.

l. How much reactance must be placed in series with a compound synchronous converter to make it flat-compounded at full load? At what power factor does the converter operate at full load? Determine characteristic curves obtained with this reactance.

m. Operate synchronous converters in parallel on d.-c. side (compound fields to be used). How does the load divide? How can division of load be altered? Is reactance necessary? If so, how much?

n. Compare the efficiencies of a synchronous converter on three-phase and on six-phase.

(1) Full load unity power factor.

(2) Full kv-a. 0.8 power factor, leading current and lagging current.

(3) Full kv-a. 0.6 power factor, leading current and lagging current.

Determine the efficiencies by input output method and also from losses.

o. Assuming polyphase transformer connected primaries in Y and secondaries in double-Y and neutrals interconnected, find the following curves:

(1) Efficiency of system versus output (load between lines). Synchronous converter operating with normal field.

(2) Efficiency of system versus output (load to neutral).

(3) D-c. line voltage and voltage to neutral versus output in each of above runs.

(4) Stray-power and equivalent resistance of synchronous converter.
(5) Transformer core-loss and equivalent resistance.
(6) Efficiency of synchronous converter (load between lines) determined from above runs.

p. A rotary converter is to operate at the end of a line having a reactance of approximately ½ ohm per wire. What must be the ratio of shunt to series turns to give flat compounding on the d.-c. side? Determine the following:

(1) Efficiency of system versus output.
(2) Power factor of system versus output.
(3) Ratio of a-c. voltage at converter to d-c. voltage at converter versus output.

How does the drop in voltage at full load due to armature reaction compare with the *IR* drop?

DAWES, "Electrical Engineering," vol. II, p. 333.
CHRISTIE, "Electrical Engineering," p. 369.
GRAY, "Principles and Practice of Electrical Engineering," 2nd Ed., p. 318.
LAWRENCE, "Principles of Alternating-Current Machinery," p. 393.
L. P. CRECELIUS, "Sixty-Cycle Synchronous Converters," *Trans. A.I.E.E.*, 1914, p. 353.

48

SINGLE-PHASE INDUCTION MOTOR LOAD CHARACTERISTICS

The working parts of the characteristic curves of an induction motor whether it be single-phase or polyphase, much resemble those of a direct-current shunt motor. The two types of motors are therefore adapted to similar classes of work.

Single-phase induction motors are constructed in much the same way as polyphase motors except that their stators have single-phase windings. The action of the two motors when running is very similar, but while the polyphase motor is self-starting a single-phase motor is not, since its torque, when at rest, is zero. Single-phase motors may, however, be equipped with special starting windings as noted below.

The synchronous speed of any type of induction motor is given by the frequency in cycles per minute divided by the number of pairs of poles on the motor and is independent of the number of phases. This is the speed which is often given on the name plate, the actual speed under load will be from 3 to 10 per cent. less than this according to the size and type of the motor. The difference between the synchronous speed and the actual speed is the slip. Slip should be expressed in per cent. of synchronous speed.

The complete speed torque curve of a single-phase induction motor is shown in Fig. 122.

The torque is zero at standstill and again is zero at a speed which is slightly less than synchronous speed. The working portion of the speed-torque curve is *bc*. The portion *ab* of the curve represents an unstable condition, since any decrease in speed such as would be produced by an increase in load, will cause a decrease in the torque and very quickly bring the motor to rest. If, on the other hand, the motor is running on the part of the curve

bc, a decrease in speed will produce an increase in torque and enable the motor to carry more load.

Since the torque of a single-phase induction motor is zero at rest, some auxiliary device is necessary for starting and bringing it up to a speed such that the torque developed by the motor is sufficient to run it up on the working part *bc* of the speed-torque curve. It is in this starting device that the essential difference between different makes of single-phase induction motors exists.

If an induction motor becomes overloaded while running so that its slip goes above *d*, Fig. 122, it will quickly come to rest. When this " breakdown " point, as it is called, is reached, there will be a rapid increase in current which will cause the motor to be much overheated and may even burn out the winding unless the

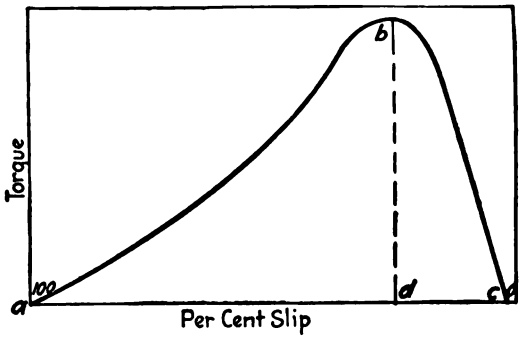


FIG. 122.

circuit is broken. The current under the conditions of breakdown may easily rise to three or four times the full-load value.

Procedure.—Inspect the motor to be used and determine the method of starting it. The motor will be provided with some form of brake or arranged as a dynamometer.

Connect the motor according to Fig. 123, being sure to follow the directions given for the connection of the wattmeter. (Page 6.)

In estimating the sizes of instruments required the efficiency may be assumed to be about the same as the efficiency of a shunt motor of corresponding size. The size of the ammeter and current capacity of the current coil of the wattmeter may be calculated by finding the full-load volt-amperes of the motor and dividing these by the rated voltage. The volt-amperes are found by dividing

the output by the efficiency and power factor. The full load power factor, as an approximation, may be assumed equal to the efficiency at full load. The current range of the instruments obtained in this way should be increased to allow for about 25 per cent. overload. The voltage range of the wattmeter should be at least equal to the rated voltage of the motor.

The speed should be obtained by subtracting the slip in revolutions from the synchronous speed calculated from the frequency of the circuit, as read on a frequency meter, and the number of motor poles. If no method is provided for counting slip, speed must be obtained directly.

The simplest way of obtaining the slip directly is by means of a stroboscopic disk illuminated by an arc light which is operated

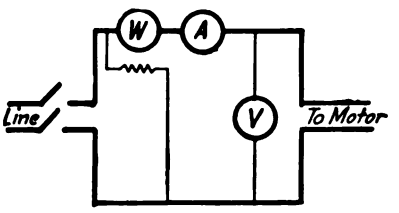


FIG. 123.

from the same circuit as the motor. A disk having alternate black and white sectors, the number of black sectors being equal to the number of poles on the motor, is attached to the motor shaft and illuminated by an arc light which is operated from the same circuit as the motor so that the current supplied to the arc and to the motor have the same frequency.

The light from an alternating arc is not steady but fluctuates, having a maximum for each maximum of the current wave. Suppose the motor has six poles: if it were to run at synchronous speed it would make one revolution in the time of three complete cycles or six alterations. In this time the light from the arc would have six maxima. Also suppose that when the light is a maximum one of the white sectors of the stroboscopic disk is at the top, it would at that instant be illuminated. One alternation later, the light will again be a maximum. In this time the disk will have made one-sixth of a revolution so that the next white sector will now be at the top. If the motor were to continue to run at synchronous speed, every time the light from the arc was

a maximum a white sector would be at the top and the disk would appear to be at rest.

If the motor runs at less than synchronous speed, the white sectors will not have time between two successive maxima of the arc to move a distance equal to the distance between two white sectors on the disk. Under these conditions, the disk will appear to move slowly backward and apparently make one revolution in the time required for the motor rotor to fall one revolution behind its synchronous speed. If the apparent speed of revolution of the disk is counted and the frequency of the circuit is measured, the actual speed of the motor may be determined accurately. If p, f, and n are the number of poles on the motor, the frequency of the circuit, and the apparent speed of revolution of the disk in revolutions per minute, the actual motor speed will be $\frac{60f}{p/2} - n$. In case a slip meter is used read description under "Three phase Induction Motor Load Characteristics," page 283.

Having wired up the motor, short-circuit the ammeter and current coil of the wattmeter and bring the motor up to speed. There should be no load on the motor while starting. Carefully remove the short-circuit from the wattmeter. If it reads backwards, short-circuit it again and reverse its current-coil connections.

Increase the load to about 25 per cent. overload, then holding the load constant by the brake count the apparent speed of the stroboscopic disk. Also record the readings of all instruments including the frequency meter. Decrease the load slightly and repeat. Proceed in this way, taking readings about every eighth of full load, until zero load is reached.

Results Required.—

a. Curve of efficiency against horse-power output.
b. Curve of torque against horse-power output.
c. Curve of power factor against horse-power output.
d. Curve of current against horse-power output.
e. Curve of slip against horse-power output.
f. Calculate the magnitude of a condenser which, when connected in parallel with the motor will make the power factor of the line unity at full load. With a condenser of this size, what would be the power factor of the line at ¼ load? At ½ load? At

$\frac{3}{4}$ load? Is the wave form of the current in the condenser the same as that in the motor?

g. How are the operating characteristics of a single-phase induction motor affected by a reduction of 10 per cent. in the line voltage?

h. If the single-phase induction motor operates 10 hours a day and delivers $\frac{1}{4}$ load for 2 hours, $\frac{1}{2}$ load for 3 hours, $\frac{3}{4}$ load for 2 hours, full load for 2 hours, and $1\frac{1}{4}$ load for 1 hour, what will be the total input per day in kilowatt hours? What is the all-day efficiency? If the motor feeder has a resistance of $\frac{1}{2}$ ohm and a reactance of one ohm, with what capacitance must the induction motor be shunted to make the voltage regulation at the motor a minimum?

i. Assuming single-phase repulsion induction motor available, determine the brush position which gives the maximum torque for full-load current (motor blocked). Determine curves of efficiency, slip, and power factor against output. What capacitance should be placed in parallel with the motor to make the power factor at that line unity when the motor is carrying full load?

LAWRENCE, "Principles of Alternating-Current Machinery," p. 511.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. II, pp. 180, 186.

CHRISTIE, "Electrical Engineering," p. 350.

DAWES, "Electrical Engineering," vol. II, p. 292.

GRAY, "Principles and Practice of Electrical Engineering," 2nd Ed., p. 308.

M. MILCH, "Repulsion Induction Motors," *Trans. A.I.E.E.*, 1906, p. 269.

F. CREEDY, "A Sketch of the Theory of the Adjustable Speed, Single-Phase Shunt Induction Motor," *Trans. A.I.E.E.*, 1909, p. 475.

E. F. W. ALEXANDERSON, "Repulsion Motor with Variable-Speed, Shunt Characteristics," *Trans. A.I.E.E.*, 1909, p. 511.

B. G. LAMME, "A Physical Conception of the Single-Phase Induction Motor," *Trans. A.I.E.E.*, 1918, p. 627.

49

THREE-PHASE INDUCTION MOTOR LOAD CHARACTERISTICS

With the exception of the speed-torque curve, the characteristic curves of a polyphase induction motor do not differ essentially from those of a single-phase induction motor. The speed-torque curves of the two types of motors, however, differ materially at their two ends especially at the end corresponding to rest or 100 per cent. slip. While the torque of a single-phase induction motor is zero at rest, the torque of the polyphase motor has a definite positive value, depending in magnitude upon the design of the motor. The difference between the upper ends of the torque curves is of no great importance. The difference is in the speed at which zero torque is reached. In the case of the single-phase motor it is slightly below synchronous speed.

Since the torque of polyphase motors is not zero at rest or 100 per cent. slip, polyphase induction motors are self-starting under light load or no load and may even be made self-starting under load if designed for that purpose.

The speed-torque curve of a polyphase motor is shown in Fig. 124. The motor operates on the part *bc* of the curve. The part *ab* representing, as in the case of the single-phase motor, an unstable condition. The ordinate *da* is the torque at rest. If this is greater than the torque necessary to overcome the opposing torque of the load and the friction of the motor, the motor will speed up until a condition of stability is reached on the part *bc* of the curve. The position of the point *b* of maximum torque with respect to speed depends upon the resistance in the rotor circuit. Increasing the resistance moves this point *b* to the left; decreasing the resistance moves *b* to the right. By adding the proper amount of resistance to the rotor circuit, it is possible to make the maximum torque occur at starting. The effect of adding increasing amounts of resistance to the rotor circuit is shown in Fig. 125. Since the speed regulation of the motor depends upon

the slope of that portion of the curve between the point of maximum torque and synchronous speed, it is obvious that besides decreasing the efficiency, the addition of resistance to the rotor of

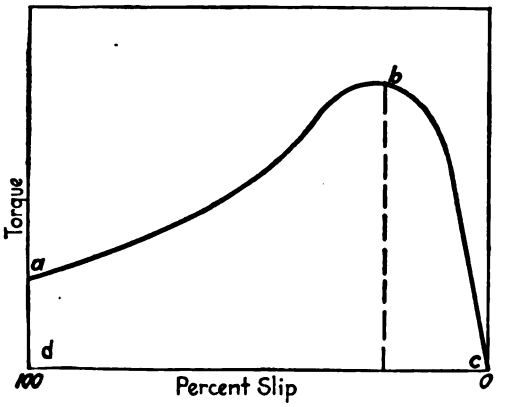


FIG. 124.

an induction motor makes the speed regulation poor. The effect is much the same as that produced by adding resistance to the armature circuit of a d-c. shunt motor.

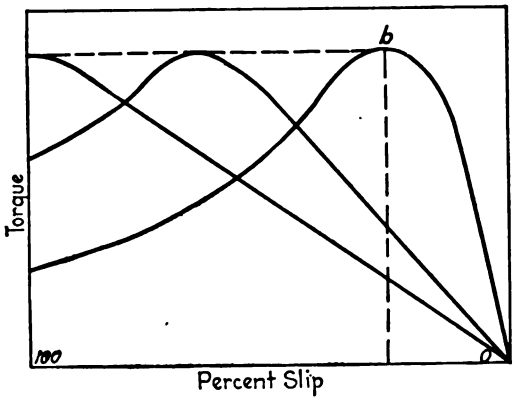


FIG. 125.

Polyphase induction motors which are to be started under heavy load have their rotors wound with the terminals of the windings brought out to slip rings so that resistance may be inserted in the rotor circuit while starting. This resistance, if used solely for starting, should be cut out when the motor is up to speed. In this

case it is sometimes placed in the rotor itself and arranged so that it may be cut out by hand after the motor is up to speed. If resistance is to be used for varying the speed of the motor, it must be placed external to the rotor in order to provide sufficient radiating surface to dissipate the heat developed in the resistance.

When the motors do not have to start any very great load and close speed regulation is required, they should have squirrel-cage rotors and should be started on low voltage which is usually obtained by the use of a compensator which is virtually a three-phase auto transformer.

Procedure.—Examine the motor assigned and determine by inspection the type of rotor used and the method by which the motor is to be started. A brake will be used for applying load, and an arc and stroboscopic disk or slip meter for determining the slip. (See experiment on "Single-phase Induction Motor Load Characteristics" for a description of stroboscopic disk.)

The vital part of a slip meter is a small motor, which, when connected to the same mains as the induction motor under test, will run at a speed equal to the synchronous speed of the induction motor. Since an induction motor has some slip, the speed of the slip motor will always be slightly greater than that of the induction motor. A common type of slip meter has two shafts mounted in line; one being driven by the induction motor and the other by a small synchronous motor. The ends of these shafts carry metallic contacts which complete the circuit through the shafts once for each revolution difference in their speed. If a series circuit is made including the shafts with their contacts, a source of electromotive force and a lamp, the lamp will flash once for each revolution in speed gained by one shaft over the other. If the shafts revolve in the same direction the number of flashes made by the lamp per minute will be equal to the slip of the motor in revolutions per minute.

In another type of slip meter the two shafts are connected through a differential gear. If the shafts are then turned in opposite directions the yoke carrying the pinions will revolve at one-half the difference in speed of the two shafts. This yoke is geared to an auxiliary shaft which runs at twice the speed of the yoke and thus at the actual difference in speed of the induction motor and the slip motor. The slip may then be obtained by means of a revolution counter.

Read what is given under " Measurement of Power in Three-phase Circuits," page 9, then connect the motor according to Fig. 126, using the two-wattmeter method for measuring the power input. Assumptions similar to those made in the experiment on the " Single-phase Induction Motor Load Characteristics " may be made in regard to the power factor and efficiency for estimating the sizes of instruments required.

Having made the proper connections, short-circuit all current coils of the instruments and bring the motor up to speed. If the motor has self-contained armature resistance, be sure to cut this out as soon as the motor has speeded up. Put about 25 per cent. overload on the motor and allow it to run for ten or fifteen minutes, then record the readings of the two wattmeters, the three amme-

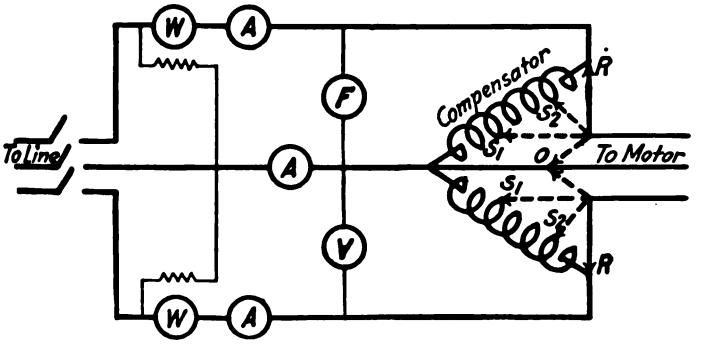


FIG. 126.

ters, the voltmeter, the frequency meter, the balance reading and the slip. If the voltage of the circuit is not exactly balanced, record the voltage between three pairs of lines. Do not fail to record the proper sign, plus or minus, with each wattmeter reading. Decrease the load slightly and take another set of readings. Proceed in this way until zero load is reached, then shut down the motor and get the zero reading of the brake.

Results Required.—

Plot curves of:

a. Efficiency and output.

b. Torque and output.

c. Average line current and output.

d. Speed and output.

e. Power factor and output.

f. Wattless component of line current and torque.

g. Real component of line current and torque.

h. Compare the characteristic curves of this motor with those of a shunt motor, making all proper allowance for any difference in the ratings of the motors compared.

i. Calculate the constants of three equal impedance coils which will replace the motor and draw the same current at the same power factor that the motor takes at full load. What should these impedances be if they are connected in delta instead of in Y?

j. A three-phase induction motor with a squirrel-cage rotor is used to convert single-phase to three-phase. Determine the vector relations of current and voltage in the line of a three-phase-induction motor which is operating from a similar motor running as a phase converter, with (1) zero load on motor, (2) one-half load on motor, (3) full load on motor. Draw a vector diagram representing conditions in single-phase line and phase converter for above conditions (1), (2), (3). Determine efficiency of motor and system for above conditions.

k. An induction motor with a wound rotor is to be used as a frequency changer. Impress one-half rated voltage on the stator and with the rotor blocked adjust load on rotor until rated current flows. Now vary the frequency by driving the rotor with a shunt motor and keep rotor voltage constant by varying voltage impressed on stator. This run is made at constant full load on rotor. Cover maximum range of frequency. Plot (1) mechanical input, (2) electrical input, and (3) efficiency against frequency.

l. How are the operating characteristics of a three-phase induction motor affected by a 10 per cent decrease in frequency, the voltage to be rated value at all times?

m. How are the characteristics altered by a reduction of 20 per cent. in voltage at rated frequency?

HUDSON, "Engineering Electricity," chap. 15.

CHRISTIE, "Electrical Engineering," p. 346.

LAWRENCE, "Principles of Alternating-Current Machinery," p. 496.

GRAY, "Principles and Practice of Electrical Engineering," 2nd Ed, p. 296.

DAWES, "Electrical Engineering," vol. II, p. 243.

Considerable material on Induction Motor Load Runs will be found in *Trans. A.I.E.E.*, 1913, part I.

THREE-PHASE INDUCTION MOTOR SPEED-TORQUE CURVES

Before proceeding with this experiment, read what is given under "Measurement of Power in Three-phase Circuits," page 9, and under the "Three-phase Induction Motor Load Characteristics."

The rotor of the motor to be tested has a three-phase winding which has its terminals brought out to slip rings. The speed is changed by altering the amount of resistance connected between the three pairs of slip rings by means of a drum-type controller. The maximum speed is obtained with the slip rings short-circuited.

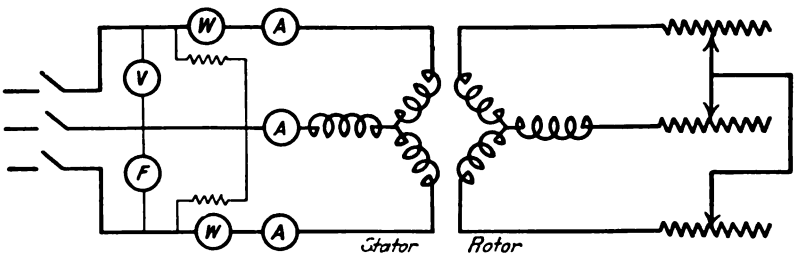


FIG. 127.

The torque of the motor is measured by a brake. The speed is to be obtained in the usual way, by counter or speed indicator.

Procedure.—After the instruments have been properly connected, short-circuit all current coils of the instruments, loosen the brake, and bring the motor up to full speed.

With the controller in the position for maximum speed, gradually load the motor, taking readings of frequency, speed, torque, current, voltage and power. Readings should be taken at six or eight loads between no load and the load which corresponds to 125 per cent. rated current. When the ammeters indicate rated

current take all readings necessary for calculating efficiency and power factor.

Repeat above procedure with the controller set at the mid-position and finally repeat again with the controller at the position for minimum speed.

Make a run keeping the torque constant at the value corresponding to rated current for maximum speed and take readings of current and speed for each controller position.

Results Required.—

Plot curves (using per cent. of synchronous speed as abscissæ) showing the relation between torque and per cent. of synchronous speed for

a. Controller set for maximum speed.

b. Controller set for intermediate speed.

c. Controller set for minimum speed.

d. Calculate also the power factor and efficiency at full load from data taken in each of the above runs.

e. Plot the curve of current versus per cent. of synchronous speed for the constant torque condition and explain why it is not a straight line.

f. Determine a curve showing the relation between starting torque and external rotor resistance. For a fixed rotor resistance how does the torque vary with the impressed voltage? Do not in any case allow more than 125 per cent. rated current to flow.

CHRISTIE, "Electrical Engineering," p. 347.
LAWRENCE, "Principles of Alternating-Current Machinery," p. 465.
PENDER, "Handbook for Electrical Engineers," p. 1009.
"Standard Handbook for Electrical Engineers," (7) 271 et seq.

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CIRCLE DIAGRAM OF THE POLYPHASE INDUCTION MOTOR

The reaction on the stator of the current in the rotor of a polyphase induction motor is exactly the same as the reaction on the primary of the current in the secondary of an ordinary static transformer feeding a non-inductive load. The induction motor is equivalent to a transformer feeding a non-inductive load and may be treated like a transformer. Its losses and efficiency may be found in exactly the same way as for a transformer from two sets of measurements made under conditions which correspond approximately to an open-circuit run and a short-circuit run on a transformer.

At no load the input to an induction motor is equal to its core loss, the friction and windage losses and the primary and secondary copper losses. Under no-load conditions the secondary copper loss is negligible on account of the small rotor current. Except, therefore, that the friction and windage losses are included, the input to the stator of an induction motor under no-load conditions corresponds to the input to a transformer when the secondary is open. The input to the induction motor when the secondary is blocked is the same as the input to a transformer when its secondary is short-circuited. The impressed voltage, of course, must be reduced when measuring the input to an induction motor with its rotor blocked to prevent excessive current, but it need not be reduced so much as for a transformer on account of the high impedance of the stator and rotor circuits. The voltage impressed on the primary of a transformer when its secondary is short-circuited or on the stator of an induction motor with its rotor blocked is the impedance voltage, i.e., the total impedance drop in both windings. The impedance voltage is usually given for full-load current and is expressed in per cent. of rated voltage. The impedance

voltage of a transformer for full-load current is generally in the neighborhood of 5 per cent. For an induction motor it is from 15 to 20 per cent.

Let P_n be the no-load input at rated voltage and frequency of a polyphase induction motor and let P_b' be the input at rated frequency for full-load stator current with the rotor blocked. Then the efficiency at full-load current to a fair degree of approximation is,

$$\text{Efficiency} = \frac{\text{Rated Output}}{\text{Rated Output} + P_n + P_b'}.$$

P_n, P_b' and the output must of course be expressed in the same units.

The complete operating characteristics of an induction motor may be obtained from P_n, P_b' and its stator resistance by means of the so-called circle diagram.

Let P_n, I_n, and V_t be the total input, the line current and the line voltage when the motor is running at no load and rated frequency. V_t must be the rated voltage of the motor.

Let P_b', I_b' and V_b be the total input, the line current and the line voltage when the rotor is blocked with full frequency but reduced voltage impressed on the stator. If V_t is the rated voltage, the blocked current at rated voltage is approximately

$$I_b = I_b' \frac{V_t}{V_b}.$$

This value of the blocked current will be used. The power factor with the rotor blocked will not appreciably change with a change in the impressed voltage and may be found for full voltage from the data obtained with the rotor blocked.

If the motor is three-phase and is Y-connected:

For no load at rated voltage and frequency:

- Phase current $= I_n$
- Phase voltage $= \frac{V}{\sqrt{3}}$
- Power input per phase $= \frac{P_n}{3}$
- Power factor θ_n, $= \frac{P_n}{\sqrt{3} V_t I_n}$

Phase current $= I_l \frac{I_p}{I_l}$

Phase voltage $= \frac{V_l}{\sqrt{3}}$

Power input per phase $= \frac{P_1}{3}$, $\frac{V_l}{V_p}$

Power factor $\cos\phi_p = \frac{P_1}{\sqrt{3} V_l I_l}$

Number of turns, voltage and frequency

If the curve is Y-connected the results may be written out as if it were Y-connected. In this case the currents and voltages used will be those of the equivalent Y-connected motor. The actual efficiency curve will not be altered by this assumption.

The circle diagram may be constructed from the data given above and the stator resistance. The proof of the diagram may be found in "Alternating Current Motors" by McAllister or in "Principles of Alternating Current Machinery" by Lawrence. The construction of the diagram is given in most textbooks for electrical engineers. The circle diagram is shown in Fig. 15A. The method of drawing the circle diagram follows.

Choose any convenient scale for current such as A amperes to the inch. The scale chosen is one that must be such as to give a diagram which can be conveniently handled. The line OI_n, which represents the normal phase current, should be at least 3½ inches and preferably longer in order to obtain accurate results. OI_l is the normal current and is the phase current of the motor when running with full voltage impressed.

Draw vertical line OV Fig. 15A first which to measure power-factor angles. Draw the line OI_n making an angle ϕ_n with OV equal to the normal power-factor angle. Make OI_n equal to the normal phase current at rated voltage and frequency. Draw OI_l making an angle ϕ_l with OV equal to the power-factor angle under the locked condition. Make OI_l equal to the locked current per phase for rated voltage and frequency. The two angles ϕ_n and ϕ_l may be laid off directly from their values which are equal to the power factor under the two conditions.

Through the points I_n and O draw lines I_nI' and OI' both perpendicular to OV. Then with I_nI' as a diameter, draw the semi-

circle $I_nI_1I_bh$ through the fixed points I_n and I_b. The center of this circle will be where a perpendicular drawn to the middle of the chord I_nI_b intersects the diameter I_nh. The easiest way to erect the perpendicular is to strike the four arcs, j, k, l and m of any convenient radius using I_n and I_b as centers. A line drawn through the intersection of the arcs j and k, and l and m will be the perpendicular.

Through I_b draw I_bg perpendicular to I_nh and lay off gf in inches equal to the blocked I^2R loss per phase in the stator divided by the product of the current scale in amperes per inch and the phase voltage of the motor. If the motor is three-phase and Y-connection is assumed, R will be equal to one-half the resistance

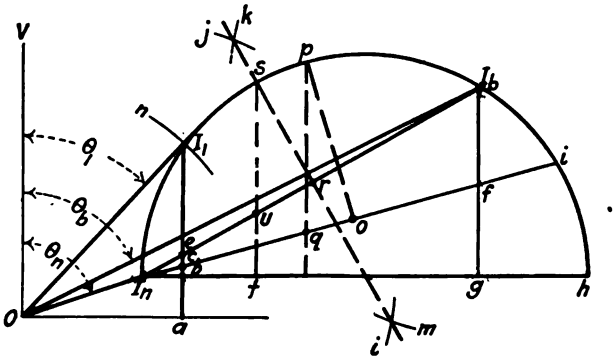


FIG. 128.

of the stator winding measured between terminals. For Y-connection,

$$gf = \frac{I_b^2 R}{K\frac{V_t}{\sqrt{3}}},$$

where I_b = line current for rated voltage and frequency with blocked rotor;

K = chosen current scale in amperes per inch;

V_t = rated line voltage.

The diagram is completed by drawing I_nI_b and I_nf.

To find the output, efficiency, power factor, etc., for any given current in the stator, strike an arc n with O as a center and with a radius equal to the given phase current divided by the current scale. Draw a line between O and the intersection of this arc with the semi-circle. Draw I_1a perpendicular to Oa.

Then if the motor is three-phase:

Stator phase current in amperes $= (OI_1)K$

Motor power factor $= \cos \theta_1$

Motor input in kilowatts $= (aI_1) \dfrac{\sqrt{3}KV}{1000}$

where V_t is the rated line voltage.

Motor output in horse-power $= (I_1e) \dfrac{\sqrt{3}KV}{746}$

Efficiency in per cent. $= \dfrac{(I_1e)}{(I_1a)} 100$

Pulley torque in pound feet $= (I_1c) \dfrac{\sqrt{3}KV_t}{746} \dfrac{33{,}000}{2\pi n}$

where n is the synchronous speed in revolutions per minute.

Slip in per cent $= \dfrac{(ec)}{I_1c} 100$

Stator copper loss in watts $= (bc)\sqrt{3}KV$

Rotor copper loss in watts $= (ec)\sqrt{3}KV_t$

No-load current in amperes $= (OI_n)K$

No-load power factor $= \cos \theta_n$

No-load losses in watts $= (ba)\sqrt{3}KV_t$

The maximum power factor will occur for a current which makes the current line OI_1 tangent to the semicircle.

The breakdown torque is the maximum torque. It may be found by determining the maximum length of the torque line I_1c. The maximum length of this line may be found by drawing a line, op, perpendicular to I_ni at its center. If a perpendicular to I_nh is drawn through the intersection of op with the semicircle, the length pq on this perpendicular will be the maximum length of I_1c or the breakdown torque.

Breakdown torque in lb-ft.

$$= (pq) \frac{\sqrt{3}KV_t}{746} \frac{33{,}000}{2\pi n}.$$

The maximum power will be developed when the power-output line I_1e has its maximum value. The maximum value of this line may be found by erecting a perpendicular to I_nI_b at its center. If rs is this perpendicular and st is a line drawn through s perpendicular to I_nh,

$$\text{Maximum horsepower} = (su)\frac{\sqrt{3}KV_l}{746}.$$

Procedure.—Measure the line current, line voltage and power input for rated frequency and voltage with the motor running at no load. Also measure the line current, line voltage and power input for rated frequency and voltage sufficient to cause full-load current to flow with the rotor blocked. Measure the stator ohmic resistance between terminals. It is best to measure the resistance between the three pairs of terminals and then average the results.

Results Required.—

a. Construct the circle diagram.

b. Find the output in horse-power, the torque in lb-ft., the efficiency and the slip in per cent. at full-load rated current.

c. Find the maximum torque and the maximum output.

d. If a load run has been made on this motor in a previous laboratory experiment, compare the efficiency, output, etc., obtained from the circle diagram with those obtained from the load run.

e. Calculate the equivalent circuit of this induction motor. (See " Principles of A-C. Machinery by R. R. Lawrence," Chapter 48.)

f. Calculate output, efficiency, slip, torque, and power factor for rated current, using equivalent circuit method.

KARAPETOFF, "Experimental Electrical Engineering," 2nd Ed., vol. II, p. 166.

LAWRENCE, "Principles of Alternating-Current Machinery," p. 490.

DAWES, "Electrical Engineering," vol. II, p. 270.

PENDER, "Handbook for Electrical Engineers," p. 1003.

"Standard Handbook for Electrical Engineers," (7), 199.

C. A. ADAMS, "A Study of the Hyland Machine as Motor and Generator," *Trans. A.I.E.E.*, vol. XXI, 1903, p. 519.

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THREE-PHASE INDUCTION GENERATOR LOAD CHARACTERISTICS

In general, any induction motor operating from the mains, when driven above synchronous speed becomes an induction generator and delivers electrical energy to the mains. The single-phase induction generator is rarely used, the three-phase machine being the type most commonly found in practice.

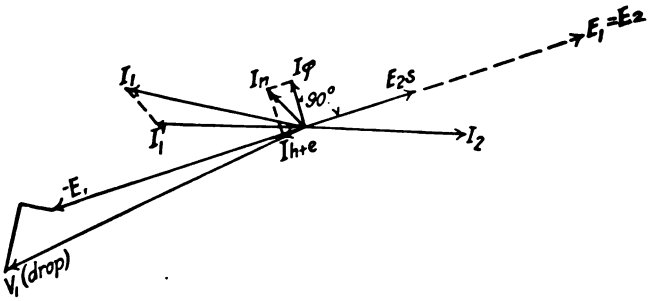


FIG. 129.

Fig. 129 shows the vector diagram of a three-phase induction motor,

where V_1 = Impressed or primary voltage drop.
$-E_1$ = Back e.m.f. (drawn as a drop).
I_1 = Primary current.
I_1' = Load or rotor component of primary current.
I_n = Vector sum of magnetizing current and the current required to supply the hysteresis and eddy-current losses.
E_{2s} = Rotor induced voltage for a slip s. (Drawn as a generated e.m.f.)
E_2 = Rotor induced voltage when blocked.
I_2 = Rotor current.

I_1' is opposite in phase to I_2 and when multiplied by the voltage $-E_1$, and the cosine of the included angle gives the power transferred to the rotor. I_1' is induced by I_2 as in ordinary transformer action.

The voltage $E_2 s$ is equal to the constant E_2 times the slip and the current is equal to this voltage divided by the rotor impedance.

If the rotor is driven at synchronous speed, the slip s is zero, consequently $E_2 s$ is zero, the rotor current zero, and I_1' zero. Under this condition no power is transferred from the stator to the rotor. The input to the stator is then equal to the stator losses.

If the speed is raised above the synchronous value the rotor inductors move in the opposite direction relative to the rotating flux than for normal speeds, consequently, $E_2 s$ is reversed in phase, and I_1' and I_2 are also reversed.

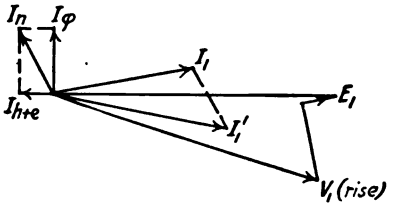


FIG. 130.

With I_1' reversed its projection on E_1 is positive and consequently generator action results.

When I_1' approaches I_{h+e} in magnitude the input to the stator approaches zero and for larger values of I_1' electrical energy is delivered from the stator terminals. In the latter case the machine is acting as an induction generator.

Fig. 130 is the vector diagram of the stator of the machine when acting as an induction generator.

Note that the current I_1 leads the terminal voltage rise V_1, whereas for induction motor action the current I_1 lagged the terminal voltage drop V_1. In changing over from motor action to generator action the current I_1' reversed in phase while the current I_n remained practically fixed.

The induction generator derives its excitation from the exciting current I_ϕ. Since I_ϕ leads E_1 by 90° the induction generator must be connected to a load which is capable of drawing as one of its components the current I_ϕ. This necessitates a condensive

load or a synchronous machine. The synchronous machine may be either an over-excited synchronous motor or an under-excited synchronous generator. The induction generator will not build up if the load is inductive. It must be condensive.

The characteristics of an induction generator are similar to those of the induction motor, and can be predetermined by a circle diagram. The load is approximately proportional to the slip, the slip being considered negative. The power factor and efficiency increase with the load. The voltage and frequency are, however, determined entirely by the connected load.

Procedure.—Connect the induction generator through a compensator or impedance to the mains and note the direction of rotation as a motor. Now connect the driving motor so as to rotate the generator in the same direction as noted above. Bring

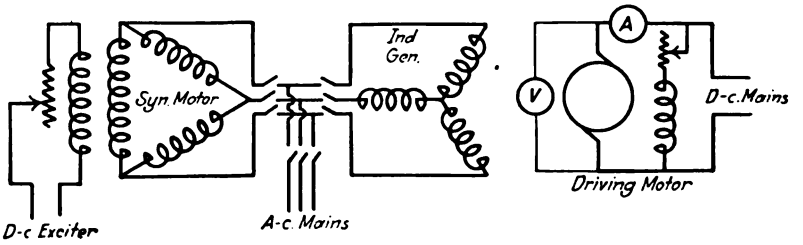


FIG. 131.

the generator up to approximately rated speed and connect the generator to the mains in the same way as above except that the impedances must be short-circuited or removed entirely. Now vary the load on the induction generator by changing the speed of the driving motor taking readings of power output, voltage, current, frequency and slip.

Now connect a synchronous motor in parallel with the induction generator, bring it up to speed and throw in field. After the motor is brought into step disconnect the mains at a point back of the parallel connection of induction generator and synchronous motor so that the generator is the only source from which the motor can draw power. Adjust the field of the motor until rated generator voltage is obtained.

Now load the synchronous motor. The frequency may be adjusted by varying the speed of the driving motor and voltage adjusted by varying the excitation of the synchronous motor.

Make a load run keeping voltage and frequency constant at rated values, and take in addition to the readings in the above run the synchronous motor field current.

With the synchronous motor operating at no load, vary its field over as wide a range as possible, taking readings of field current and generator voltage. Keep frequency constant at rated value throughout this run.

Results Required.—

a. Plot slip, power factor and line current against generator output for the case where the induction generator is connected to the mains.

b. Plot slip, power factor, line current and synchronous motor field current against generator output for the case where the generator is loaded by the synchronous motor.

c. Plot synchronous motor field current versus generator terminal voltage for the no-load varying voltage run.

d. Explain why the load delivered by an induction generator is approximately proportional to slip.

e. Why is the generator voltage fixed by the load and not by the generator itself?

CHRISTIE, "Electrical Engineering," p. 356.
LAWRENCE, "Principles of Alternating-Current Machinery," p. 497.
DAWES, "Electrical Engineering," vol. II, p. 265.
"Standard Handbook for Electrical Engineers," (7), 222.
H. M. HOBART and E. KNOWLTON, "The Squirrel-Cage Induction Generator," *Trans. A.I.E.E.*, 1912, p. 1721.

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CONCATENATION OF INDUCTION MOTORS

Two similar induction motors when operated in concatenation exhibit characteristics very similar to those of two-shunt motors connected in series, e.g., the no-load speed is one-half the rated value and the speed decreases slightly as the load increases.

Two similar wound rotor motors when direct coupled may be connected in concatenation by supplying power to the stator of motor A, and connecting the rotor terminals of A to the rotor ter-

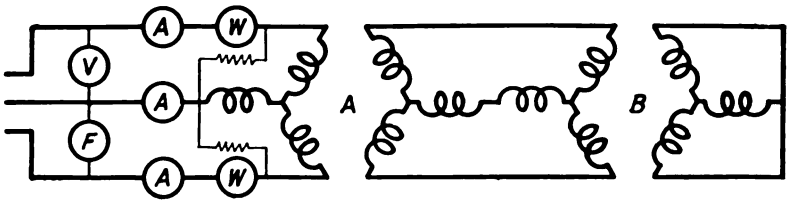


FIG. 132.

minals of B, and short circuiting the stator terminals of B. The rotor terminals must be connected in such manner that both machines tend to rotate in the same direction, otherwise motor B opposes A and the net torque is greatly reduced.

Motor B receives power through A by transformer action and at a frequency of fs_A; s_A being the slip of motor A. At no load, s_A is very slightly greater than 0.5, consequently the frequency impressed upon B is slightly greater than one-half rated value and since the speed of both motors is practically one-half rated speed, the slip of B is normal.

If the set were blocked, motor B would, except for the impedance drops in motor A, have rated voltage impressed upon its rotor. If the set were running at synchronous speed, the voltage

impressed upon the rotor B would be zero. At one-half speed the voltage of B is, neglecting impedance drops, one-half normal.

Motor A, therefore, runs on normal voltage but at approximately 50 per cent. slip, while motor B runs on approximately one-half rated voltage and normal slip.

Motor B receives its exciting current from the rotor of A, consequently A carries the exciting current for both machines. The power factor of A is consequently less than that of B.

The core losses in the stator of A are normal since the voltage and frequency are rated. Those in the rotor of A are greater than normal since the frequency is much higher than normal due to the large slip. The core-losses in B are much lower than normal due to the voltage being less than one-half rated and the frequency being approximately one-half the rated value.

The copper losses in A are greater than those in B since A carries the exciting current for B.

Synchronous speed for similar motors in concatenation is one-half the rated synchronous speed. If the set is driven above this speed, the slip of B becomes negative, motor B acts as an induction generator and opposes the rotation of A. The power generated by B is delivered to the mains by means of transformer action in A.

If the rotors are short-circuited while the set is brought up to speed under no load, rated speed will be attained, since A will be acting under normal conditions and B being short-circuited will simply act as a small load on A. If the short circuit on the rotors is now removed the set will continue to run at normal speed since the voltage impressed upon B is negligible and consequently the opposing torque due to generator action is negligible. As the load is applied, the slip increases, the opposing torque of B increases and a condition is soon reached where the set breaks down but instead of coming to a standstill as a single motor would, it drops down to approximately one-half the rated speed of one motor for at this speed the torque of B changes sign, B acts as a motor and assists A in driving the load.

The above discussion applies to two similar motors, i.e., motors having the same speed and voltage ratings. When motors of different speed ratings are operated in concatenation the speed of the set is approximately equal to $\frac{p_A}{p_A+p_B}n$, where p_A, p_B and n

are the number of poles in A, the number in B and the rated speed of A respectively.

If impedance drops and losses are neglected the general expression for speed is $\frac{p_A}{p_A+p_B}n$ and the ratio of powers delivered by the two machines is $\frac{p_A}{p_B}$ but in practice the power developed in motor B is cut down considerably by the impedance drops and losses.

Procedure.—Connect the machines in concatenation and make a load run taking readings of power input, voltage, current, frequency, slip and torque. Consider the set to be at a quarter overload when line current is 125 per cent. of rated value.

Results Required.—

a. Curve of over-all efficiency versus output of set.
b. Power factor of set versus output of set.
c. Slip of set versus output of set.
d. Combined torque versus output of set.
e. Power factor of each machine versus output of set.
f. Per cent. slip of each machine versus output of set.
g. Electrical power absorbed by each machine versus output of set.
h. Frequency of each machine versus output of set.

LAWRENCE, "Principles of Alternating-Current Machinery," p. 477.
DAWES, "Electrical Engineering," vol. II, p. 262.
"Standard Handbook for Electrical Engineers," (7), 277.

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ALTERNATING-CURRENT SERIES MOTOR LOAD CHARACTERISTICS

The armature and field of a series motor are connected in series. Consequently, if an alternating current be sent through such a motor, the current in the armature and field will be in phase at every instant. A series motor will, therefore, develop a torque, which, though intermittent, will always act in the same direction. The direction in which this torque acts depends upon the relative directions of the current in the armature and field, and it may be reversed by merely reversing the connections of either the armature or the field. Due, however, to the large core losses and high reactance of a direct-current series motor, a motor of this type will develop very little torque or power when used on an alternating-current circuit.

A series motor intended for use on an alternating-current circuit must necessarily have both its field and armature cores laminated and, moreover, in order to develop satisfactory torque and power-factor characteristics, it must have the ratio of armature to field turns relatively large. This reduces the field reactance and correspondingly increases the armature reactance but this latter can be nearly neutralized by the use of a compensating winding placed in the pole faces of the motor, in such a way as to oppose and neutralize the magnetic field, produced by the armature current.

The compensating winding may be either short-circuited on itself and receive its current by the transformer action between it and the armature, in which case the coil and the armature act inductively like a short-circuited transformer, or it may be connected in series with the armature, as it must be, when the motor is used on both alternating and direct-current circuits.

When the compensating winding is short-circuited, the motor is said to be inductively compensated; when it is in series with the

armature and the field, the motor is said to be conductively compensated.

A two-pole motor with a series-connected compensating field is shown in Fig. 133.

F and F' are the main fields.
C and C' are the compensating fields.[1]
A is the commutator.

The curved lines inside of A represent the armature winding. The straight lines joining the armature windings to the commutator are resistances. These will be mentioned later.

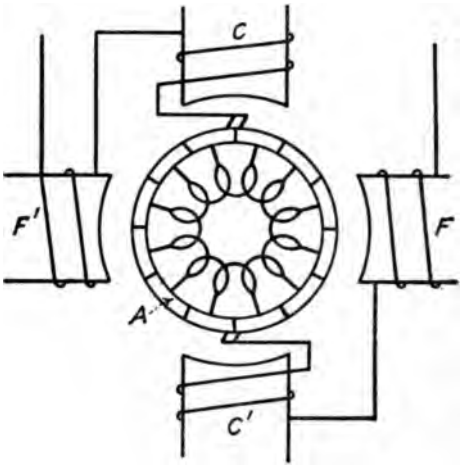


FIG. 133.

The sparking which tends to occur in a series alternating-current motor is one of the inherent difficulties in the design of a motor of this type. During commutation, the brushes on any two commutator bars short-circuit the armature coils under them. These short-circuited coils are in the most favorable position to have a current induced in them by the alternating-field flux, and unless this induced current is diminished in some way, destructive sparking and heating of the short-circuited coils and commutator will result.

[1] The compensating winding of an actual motor is not placed on separate poles as shown in Fig. 133, but is wound in slots cut in the faces of the poles carrying the main field winding. The two field windings are shown as if they were on separate poles merely for convenience in drawing the figure.

The usual way to diminish this short-circuit current is by the use of small resistances inserted between the armature coils and commutator bars. These resistances naturally increase the resistance of the armature between the brushes and, consequently increase the copper loss in the main armature circuit, but if the resistances are properly adjusted, the increase in the armature copper loss is more than balanced by the decrease in the heating in the coils short-circuited during commutation, and, moreover, commutation is rendered possible. A little thought will show that the two resistances are in parallel with respect to the external circuit, and in series with respect to the short-circuited armature coils.

Series motors for alternating-current operation are inherently low frequency machines. The use of high frequency would cause prohibitive reactance. Small alternating-current series motors

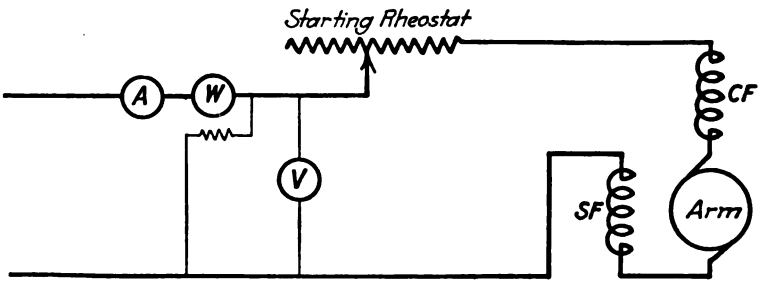


FIG. 134.

are generally controlled and have their speed varied by series resistance; large motors, however, are controlled by varying the impressed voltage by means of a compensator.

Procedure.—A friction brake will be used for loading the motor. Any series motor will increase its speed rapidly as the load on it is decreased. For this reason, care must be taken in handling the brake. The motor should be started under load, and the load must not be reduced so far as to make the speed dangerous. Ask what the safe limit of speed is for the particular motor assigned.

This test will be similar to the one on the direct-current series motor described on page 111. A wattmeter, of course, must be used for measuring the input to the alternating-current series

motor. The proper connections for the test are shown in Fig. 134. Run motor under rated conditions.

CF is the compensating field.
SF is the main series field.

The starting device or speed controller may be either a compensator or a variable resistance. Make all tests with the controller in running position.

Results Required.—

a. Efficiency versus output for 24 cycles.
b. R.p.m. versus output.
c. Torque versus output.
d. Current versus output.
e. Power factor versus output.
f. Repeat *a*, *b*, *c*, *d* and *e* operating motor on direct current.
g. Repeat *a*, *b*, *c*, *d* and *e* operating motor on 60 cycles.
h. Vector diagrams to scale representing full-load condition for 24 and 60 cycles. Use approximate diagram and a common origin. Calculate the ratio of the voltage across the armature to the impressed voltage for each case.

i. Given an a-c. series motor designed for conductive compensation: will the machine function properly when connected for inductive compensation? If not, what modifications are necessary? Compare operating characteristics.

LAWRENCE, "Principles of Alternating-Current Machinery," p. 555.
CHRISTIE, "Electrical Engineering," p. 358.
DAWES, "Electrical Engineering," vol. II, p. 279.
E. F. ALEXANDERSON, "A Single-Phase Railway Motor," *Trans. A.I.E.E.*, 1908, p. 1.
B. G. LAMME, "The Single-Phase Commutator-Type Motor," *Trans. A.I.E.E.*, 1908, p. 137.
WM. S. FRANKLIN and S. SEYFERT, "On the Space Economy of the Single-Phase Series Motor," *Trans. A.I.E.E.*, 1910, p. 23.

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SERIES WOUND THREE-PHASE COMMUTATOR MOTOR

The three-phase commutator motor has a stator like that of an induction motor and a rotor like that of a direct-current armature. The armature may be connected in series with the stator as in Fig. 135 or the armature may be supplied through trans-

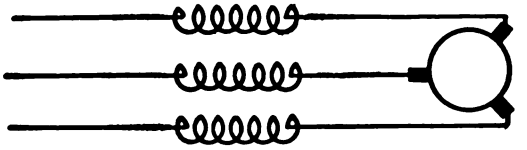


FIG. 135.

formers as in Fig. 136. The latter is preferable since the armature may be wound to give best commutating condition. The fields may be Y- or delta-connected.

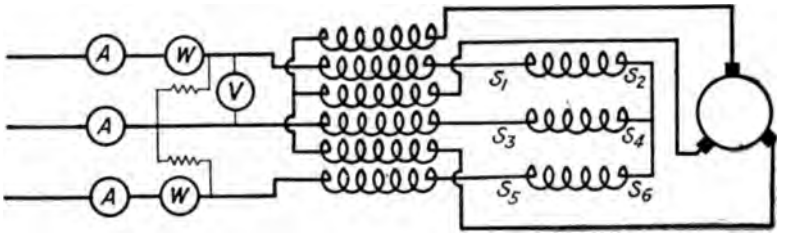


FIG. 136.

The motor has a speed-torque curve similar to that of the single-phase series motor. In a general way we may consider the motor as three single-phase motors built on the same frame. The motor is used anywhere where series characteristics are desirable. It may also be employed for regenerative braking.

Procedure.—Connect up the motor and provide for the measurement of input, by putting ammeters, wattmeters and a

voltmeter in the mains. The output may be measured by some form of brake. Record current, voltage and power input as well as speed and torque. Place a single-phase wattmeter, an ammeter and a voltmeter in each phase of the polyphase transformer to measure the power supplied to the armature. At the end of the run take data from which the copper loss and core loss in the series field may be obtained, data for finding the losses in the transformers and data for finding the losses in the armature.

Results Required.—

a. Curve of efficiency and horse-power output.
b. Curve of line current and horse-power output.
c. Curve of armature current and horse-power output.
d. Curve of power factor and horse-power output.
e. Curve of armature power factor and horse-power output.
f. Curve of speed and horse-power output.
g. Curve of torque and horse-power putput.
h. Percentage distribution of losses at full load, expressed in per cent. of input.
i. Curve of total series field loss against current.
j. Curve of total transformer loss against current.
k. Curve of total armature loss against line current.
l. Curve of speed as a function of brush position for constant torque.

V. KARAPETOFF, "The Secomor—A Kinematic Device which Imitates the Performance of a Series-Wound Polyphase Commutator Motor," *Trans. A.I.E.E.*, 1918, p. 329.

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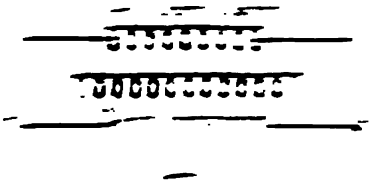
THE MERCURY ARC RECTIFIER

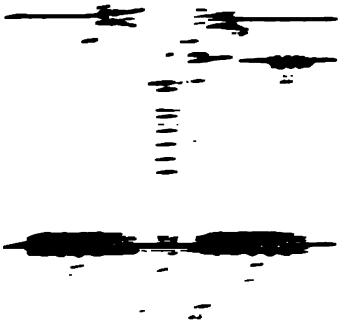
It is a well-known property that in an evacuated tube containing mercury vapor, a non-volatile electrode such as iron or graphite and one mercury electrode, unilateral conduction is obtained. The iron or graphite is the anode and the mercury the cathode. The passage of current, once it has become established, causes an arc through the tube which heats and vaporizes the mercury and thus furnishes a continuous supply of conducting vapor.

The mercury arc rectifier, Fig. 137, consists of a highly evacuated tube having two recessed iron or graphite anodes A_1 and A_2, a cathode C consisting of a pool of mercury and an auxiliary anode A_3, also consisting of mercury. The two anodes A_1 and A_2, are connected to the opposite line wires from the regulating transformer. The auxiliary anode A_3 is connected through a switch S and resistance R to either main. The cathode is connected to the load which may be a resistance or a storage battery. The reactance EF is connected across the a-c. mains and midpoint D is connected to the other side of the load.

To start the rectifier the switch S is closed and the tube is rocked until the mercury of the cathode makes contact with that of the anode A_3, causing a current to flow from line G through RA_3CBDF to line H.

When the tube rocks back the mercury circuit is broken causing an arc to be set up between C and A_1 or A_2. The switch S is now opened. If the anode A_1 happens to be positive the current will enter here, flow to the cathode, through the load B, through the reactance E which it charges and to the line G. When the voltage decreases the current is maintained by the discharge of the reactance E which makes the current lag the voltage. Consequently when the voltage wave is zero the current has a definite value, the





he negative loops turned over and made positive. The reactance, ıowever, smooths this out causing a double-frequency wave located .bove the zero axis.

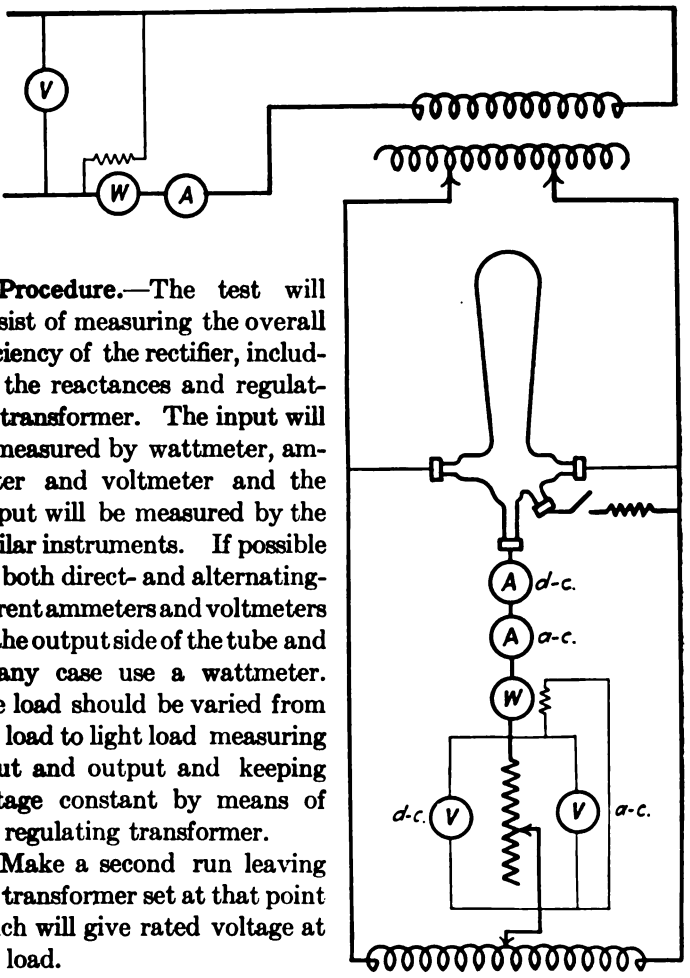


Fig. 138.

Procedure.—The test will onsist of measuring the overall fficiency of the rectifier, includ- ng the reactances and regulat- ng transformer. The input will e measured by wattmeter, am- neter and voltmeter and the utput will be measured by the imilar instruments. If possible se both direct- and alternating- urrent ammeters and voltmeters n the output side of the tube and n any case use a wattmeter. 'he load should be varied from ull load to light load measuring ıput and output and keeping oltage constant by means of he regulating transformer.

Make a second run leaving he transformer set at that point 'hich will give rated voltage at ıll load.

The percentage regulation of he tube should be expressed as he rise in voltage from full load to no load (for fixed ratio of trans- ɔrmation) referred to full-load voltage.

Take oscillograms to the same axis, of output current and volt- ge as well as current in A_1 and A_2.

Results Required.—

a. Plot of efficiency and output for constant voltage.

b. Plot of input power factor and output for constant voltage.

c. Plot of d-c. volts and output for fixed transformer ratio.

d. Regulation in per cent. of full-load voltage.

e. Explain why the product of d-c. amperes and volts does not equal the indicated watts of the wattmeters.

f. Explain why the d-c. and a-c. meters on the output side do not read the same and state which reads correctly and why.

g. Oscillograms.

h. Discussion of oscillograms.

DAWES, "Electrical Engineering," vol. II, p. 336.

"Standard Handbook for Electrical Engineers," (6), 274.

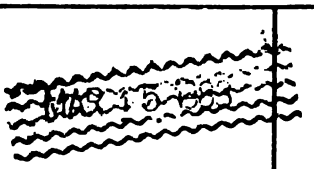
PENDER, "Handbook for Electrical Engineers," p. 1209.

C. P. STEINMETZ, "Constant-Current Mercury Arc Rectifier," *Trans. A.I.E.E.*, 1905, p. 371.

D. C. & J. P. JACKSON, "Alternating Currents and Alternating-Current Machinery," p. 895.

To renew the charge, book must be brought to the desk.

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